Exploring yrast structures in neutron-rich nuclei with deep-inelastic collisions

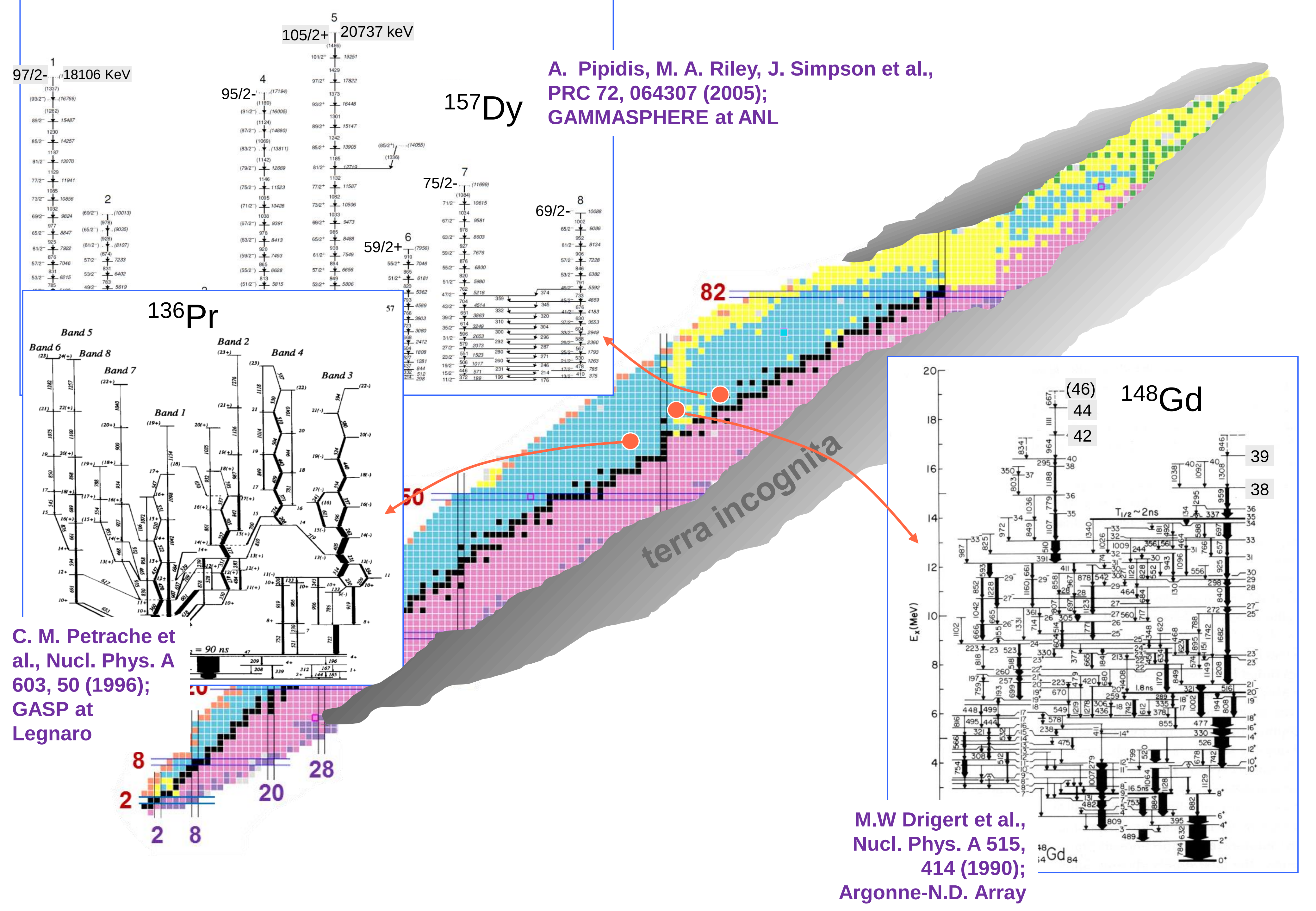
Bogdan Fornal

Institute of Nuclear Physics,Polish Academy of Sciences
Krakow, Poland

Collaboration with: ANL Argonne (USA), INFN LNL Legnaro , Univ. Padova (Italy), Purdue Univ. (USA), ANU Canberra (Australia), NSCL MSU (USA), Univ. Surrey (UK)

Reflections
on the atomic nucleus
Liverpool, 28-30 July 2015

Liverpool, 28-30 July 2015
on the atomic nucleus
Reflections

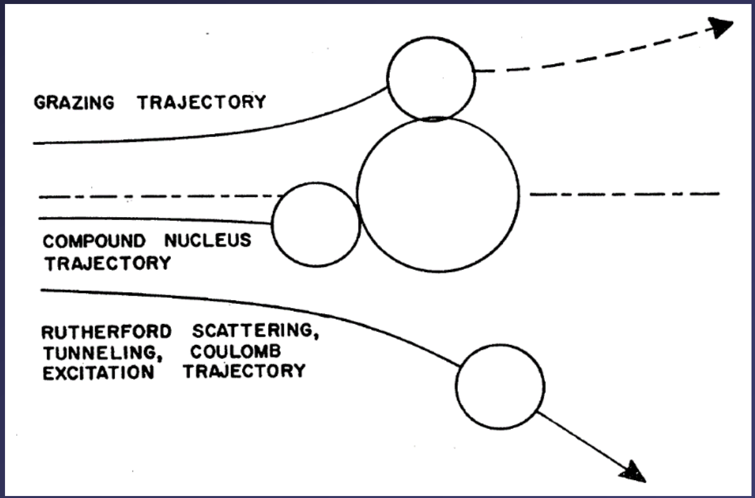

157Dy
97/2- 18106 KeV
105/2+ 20737 keV
95/2-
75/2-
69/2-
59/2+
A. Pipidis, M. A. Riley, J. Simpson et al.,
PRC 72, 064307 (2005);
GAMMASPHERE at ANL
136Pr
Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
Band 7
Band 8
C. M. Petrache et al., Nucl. Phys. A 603, 50 (1996);
GASP at Legnaro
148Gd
(46)
44
42
39
38
E_x (MeV)
$T_{1/2}$ ~ 2ns
M.W Drigert et al.,
Nucl. Phys. A 515, 414 (1990);
Argonne-N.D. Array
terra incognita
82
50
28
20
8
2
2
8
20
28

VOLUME 3, NUMBER 5 PHYSICAL REVIEW LETTERS SEPTEMBER 1, 1959

COMPLEX NUCLEON TRANSFER REACTIONS OF HEAVY IONS*

Richard Kaufmann† and Richard Wolfgang
Department of Chemistry, Yale University, New Haven, Connecticut
(Received August 12, 1959)

^{16}O (160 MeV) + ^{27}Al



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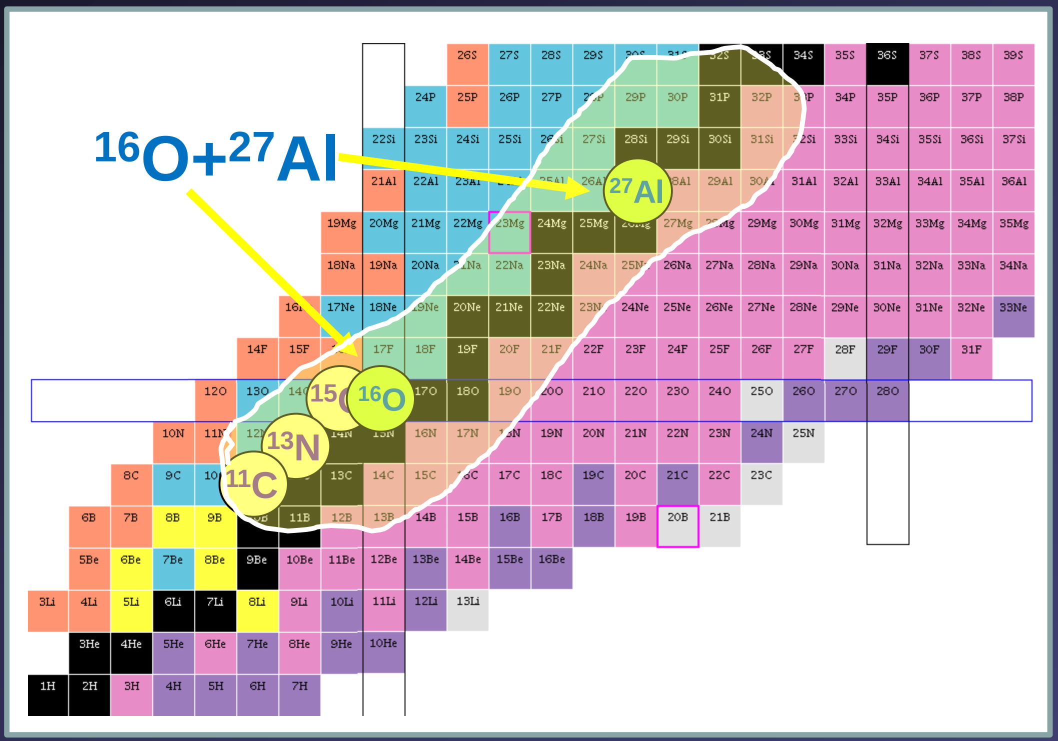
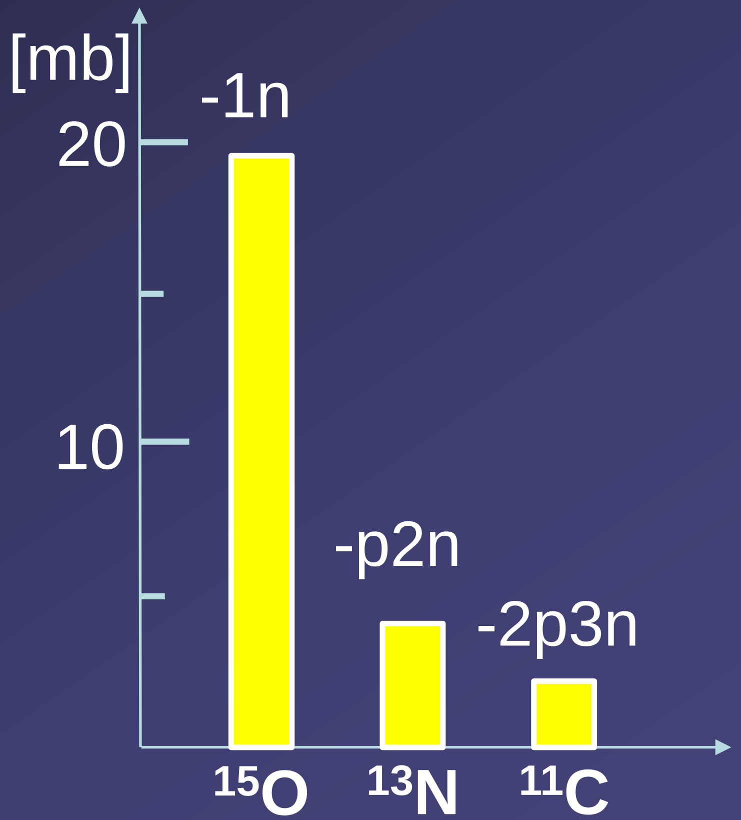
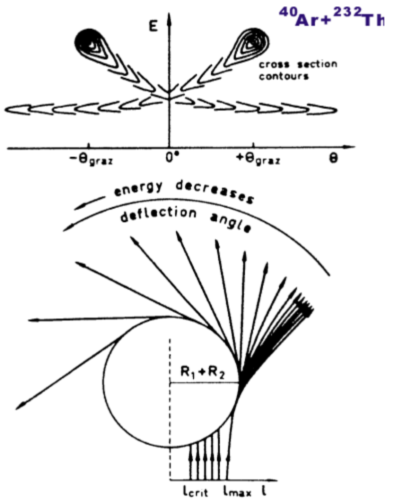




In the 1970's, extensive experimental studies of the deep-inelastic reaction mechanism were carried out and theoretical concepts were developed.

V.V. Volkov,
Deep Inelastic Transfer Reactions – the New Type of Reactions Between Complex Nuclei,
Physics Reports 44, 93 (**1978**)

Wilczynski Plot



J. Wilczynski,
Phys. Lett. B 47, (**1973**)

L.G. Moretto and R.P.Schmitt,
Deep inelastic reactions: a probe of the collective properties of nuclear matter,
Rep. Prog. Phys. Vol. 44 (**1981**)

A. Gobbi,
Different regimes of dissipative collisions in Lecture Notes in Physics, Volume 168, **1982**, pp. 159-174.

W.U.Schroeder and J.R.Huizenga,
Dumped Nuclear Reactions in Treatise on Heavy-Ion Science, Ed. D.A.Bromley. N.Y.; London. **1985**, pp 113-726.

VOLUME 38, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 1977

Angular-Momentum Transfer in Deep-Inelastic Processes

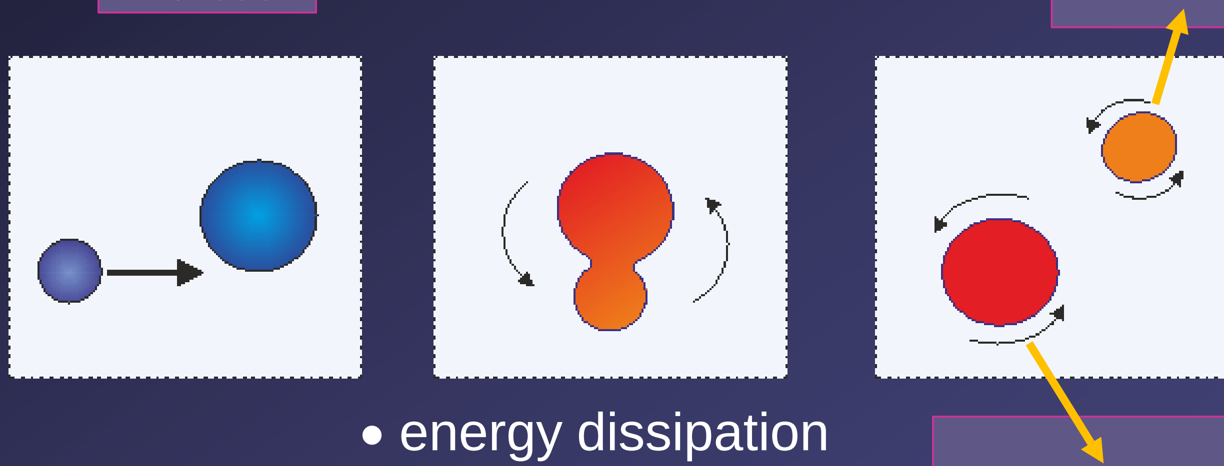
P. Gläsel,* R. S. Simon,† R. M. Diamond, R. C. Jared, I. Y. Lee,
L. G. Moretto,‡ J. O. Newton,§ R. Schmitt, and F. S. Stephens
Department of Chemistry and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 29 November 1976)

PHYSICAL REVIEW C VOLUME 20, NUMBER 3 SEPTEMBER 1979

Angular momentum transfer in the deep inelastic reactions of 237 MeV ^{40}Ar with ^{89}Y

M. N. Namboodiri, J. B. Natowitz, P. Kasiraj, R. Eggers,* L. Adler, P. Gonthier, C. Cerruti,† and S. Simon
Cyclotron Institute, Texas A & M University, College Station, Texas 77843
(Received 3 April 1979)

$$\vec{I}_{init}$$



$$\vec{I}_1 = \frac{\Im_1 \vec{I}_{ini}}{\Im_1 + \Im_2 + \Im_{tot}}$$

$$\vec{I}_2 = \frac{\Im_2 \vec{I}_{ini}}{\Im_1 + \Im_2 + \Im_{tot}}$$

- energy dissipation
- N/Z equilibration
- transfer of angular momentum

VOLUME 38, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 1977

Angular-Momentum Transfer in Deep-Inelastic Processes

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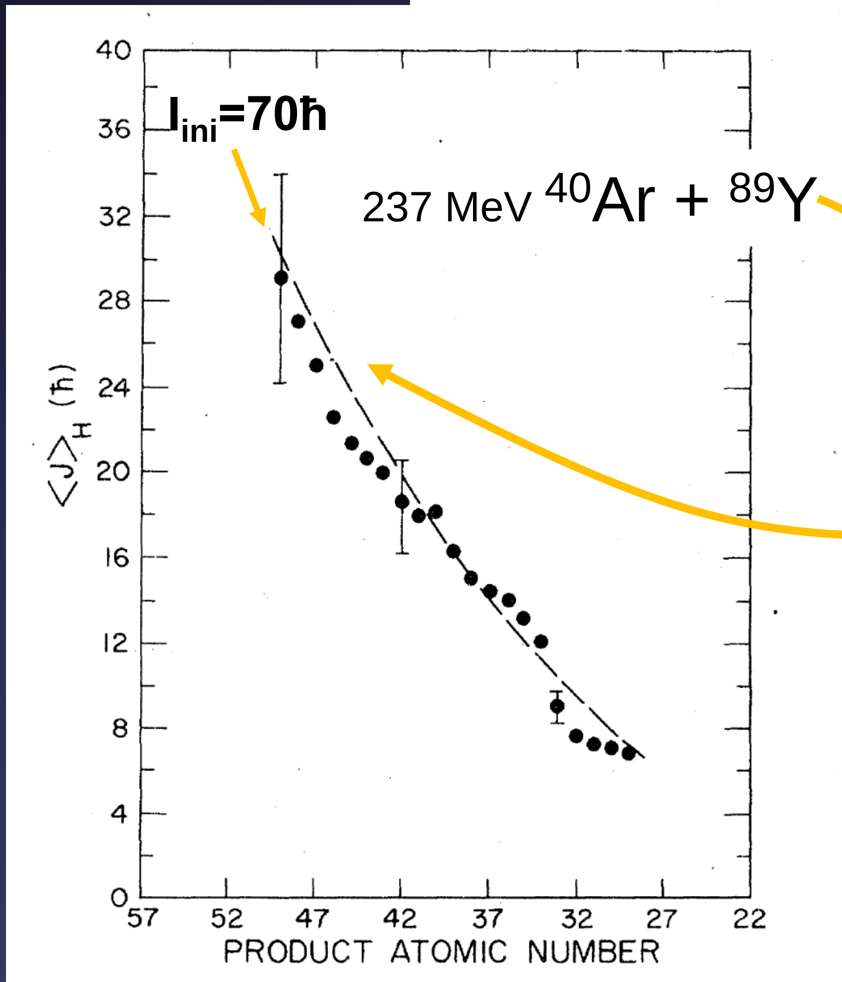
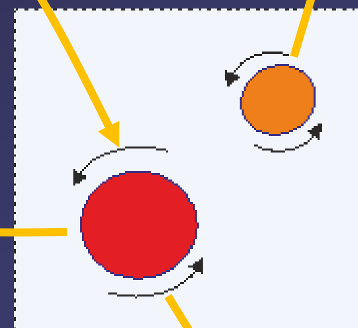


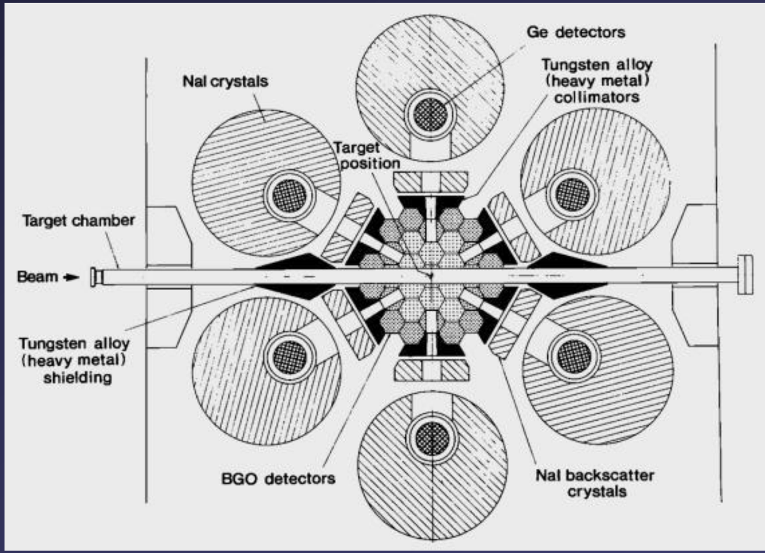
$$\vec{I}_1 = \frac{\mathfrak{I}_1 \vec{I}_{ini}}{\mathfrak{I}_1 + \mathfrak{I}_2 + \mathfrak{I}_{tot}}$$



$$\vec{I}_2 = \frac{\mathfrak{I}_2 \vec{I}_{ini}}{\mathfrak{I}_1 + \mathfrak{I}_2 + \mathfrak{I}_{tot}}$$

To be able to resolve gamma rays from high-spin states in deep-inelastic reaction products one had to wait until the advent of the efficient Compton-suppressed germanium arrays.

The **T**otal **E**nergy **S**uppression **S**hield **A**rray (**TESSA**) was developed by the **University of Liverpool** and Daresbury Laboratory; operational since **1983**



TESSA: A MULTIDETECTOR gamma-RAY ARRAY DESIGNED TO STUDY HIGH SPIN STATES

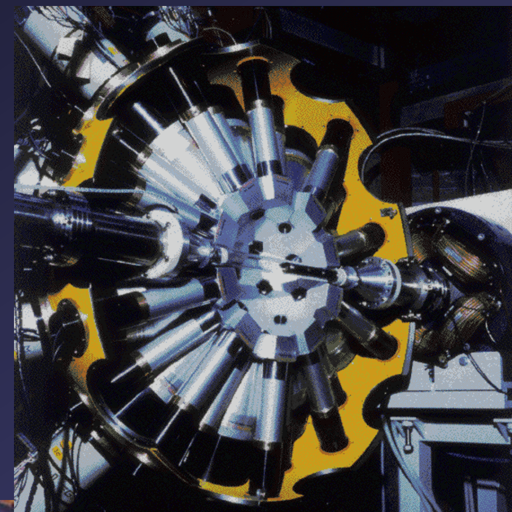
P.J. Twin (Liverpool U. & Daresbury) , **P.J. Nolan, R. Aryaeinejad, D.J.G. Love, A.H. Nelson, A. Kirwan** (Liverpool U.)

Nucl. Phys. A409 (1983) 343

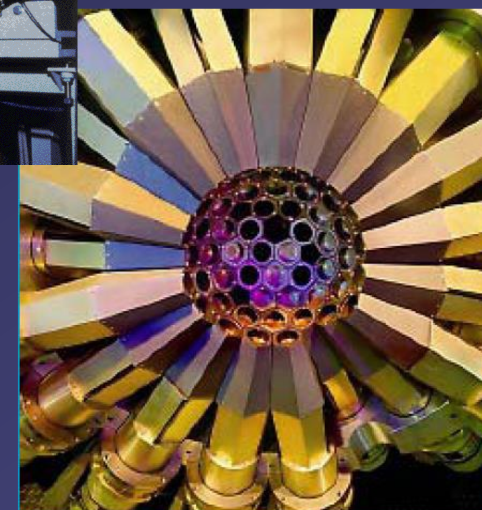
Gamma-ray arrays based on Compton supressed Ge detectors

Starting from the 80’s:

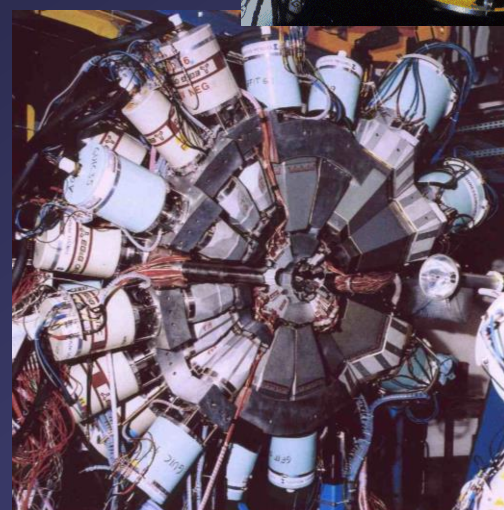
TESSA (**Liverpool**-Daresbury),
OSIRIS (Berlin),
ARGONNE-ND ARRAY (Argonne)
NORDBALL (Copenhagen),
JUROSPHERE (Jyvaskyla),
EUROGAM (Strasbourg),
CLARION (Oak Ridge)
GASP (Legnaro-Padova)
EUROBALL
GAMMASPHERE



GASP
Legnaro

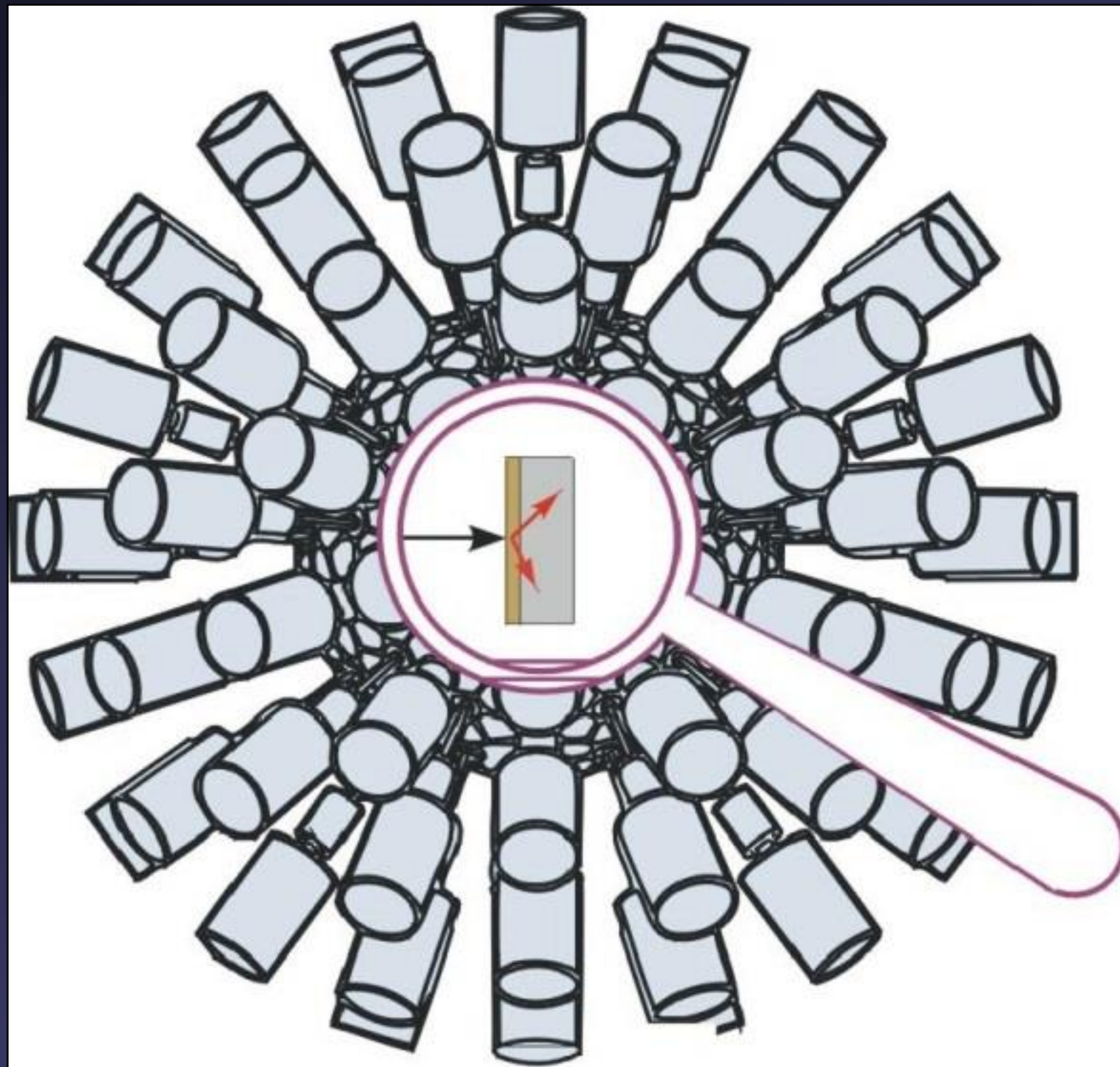


GAMMASPHERE
Argonne, Berkeley



EUROBALL
Legnaro, Strasbourg

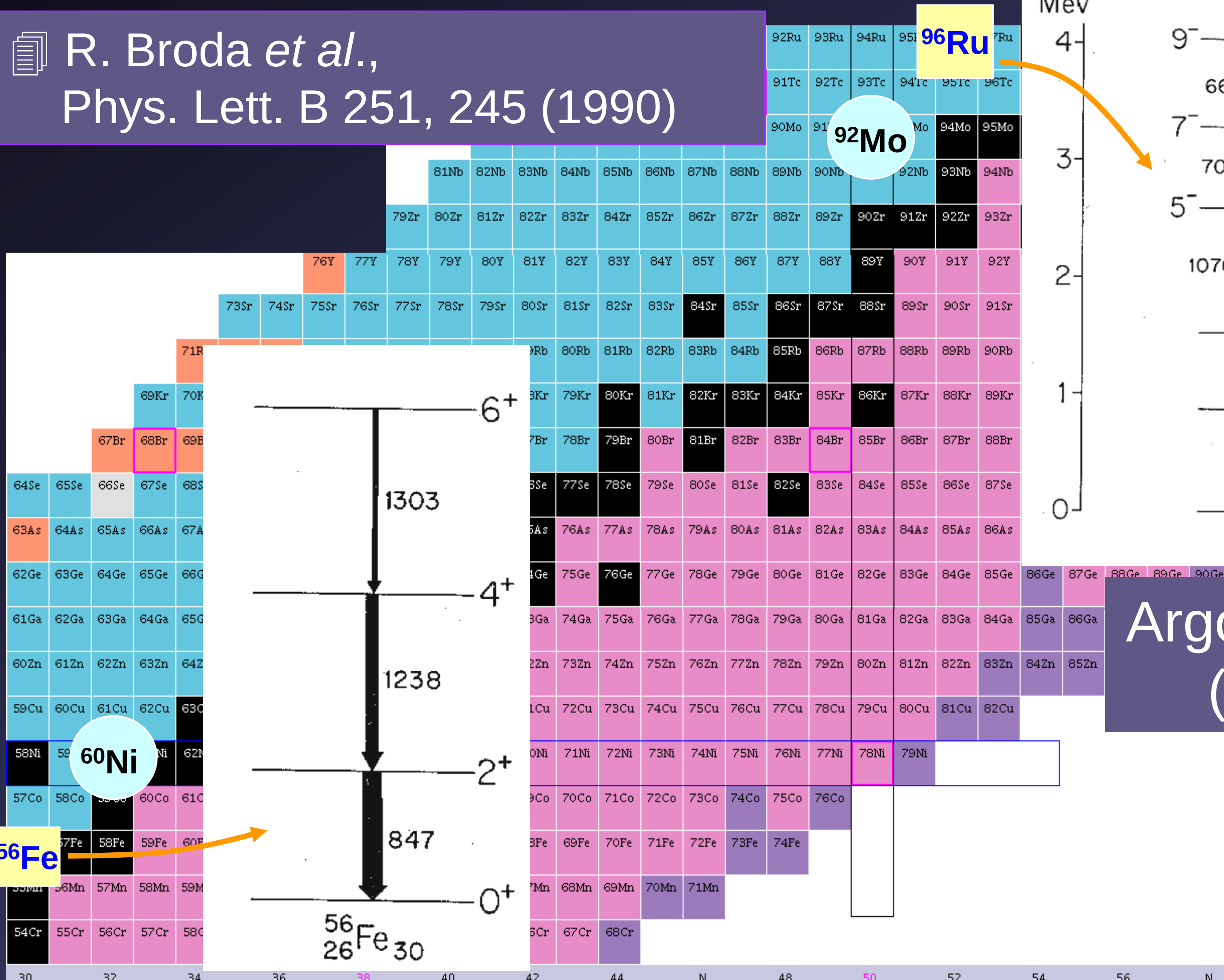
Measuring gamma rays from deep-inelastic reaction products by using the thick-target technique

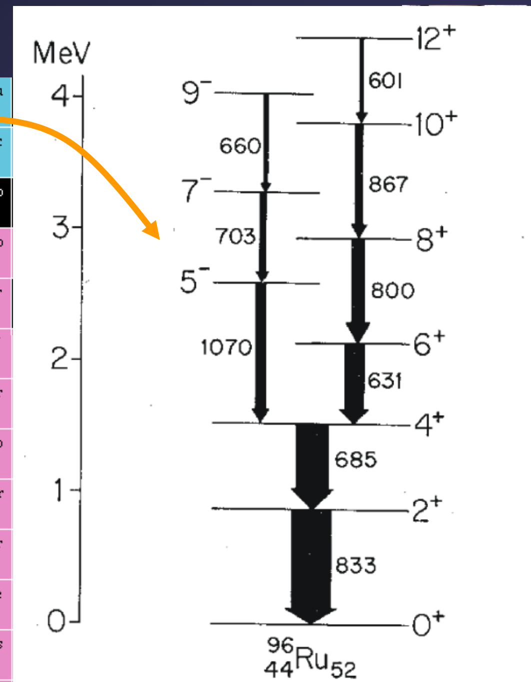


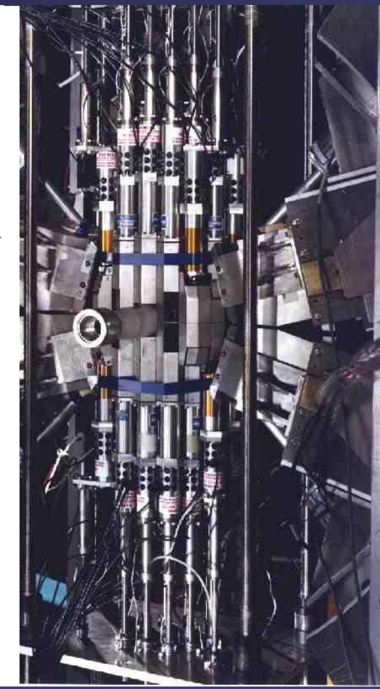
Discrete gamma-ray spectroscopy with deep-inelastic heavy-ion collisions – thick target technique:

^{60}Ni(255 MeV)+^{92}Mo

R. Broda *et al.*,
Phys. Lett. B 251, 245 (1990)



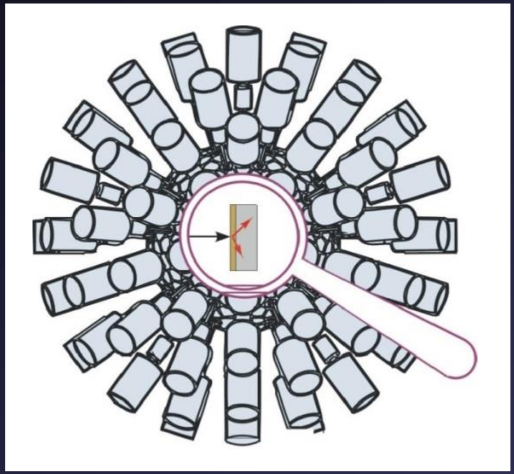


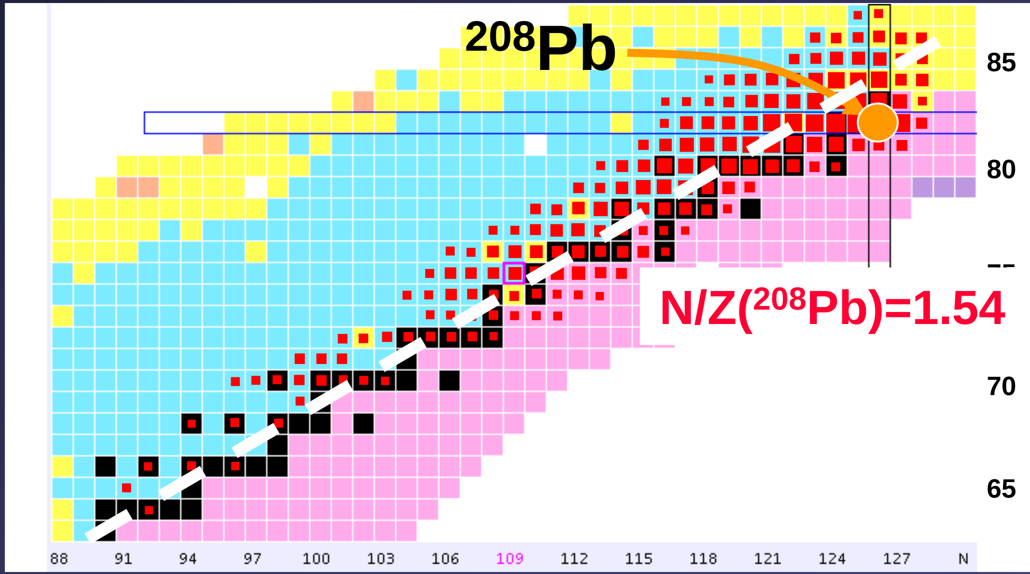


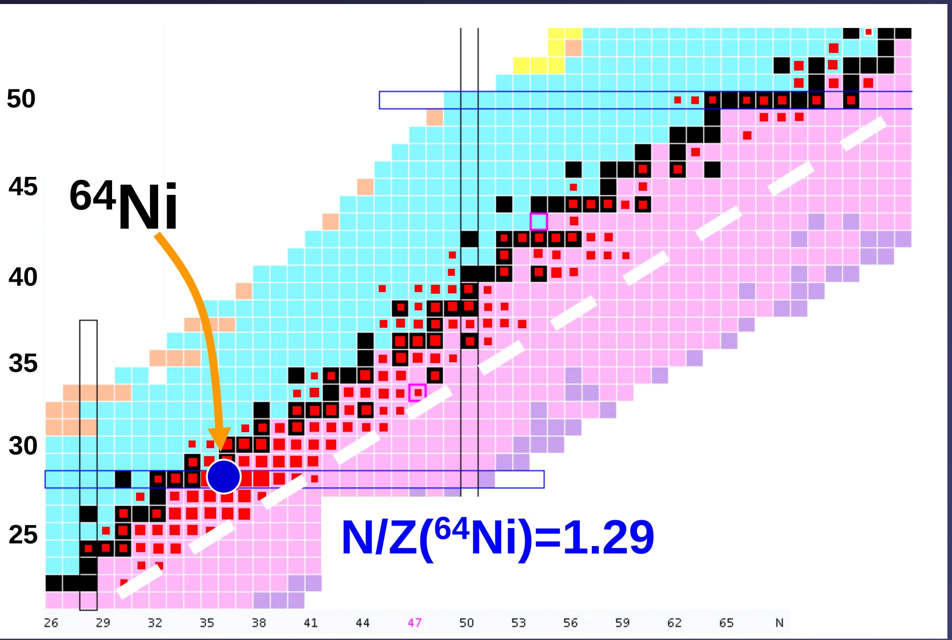
Argonne-Notre Dame Array
(12 HPGe+ 50 BGO)

Detailed product yield distribution measured by using the gamma-gamma concidence with thick-target for the system:

^{64}Ni + ^{208}Pb at 350 MeV

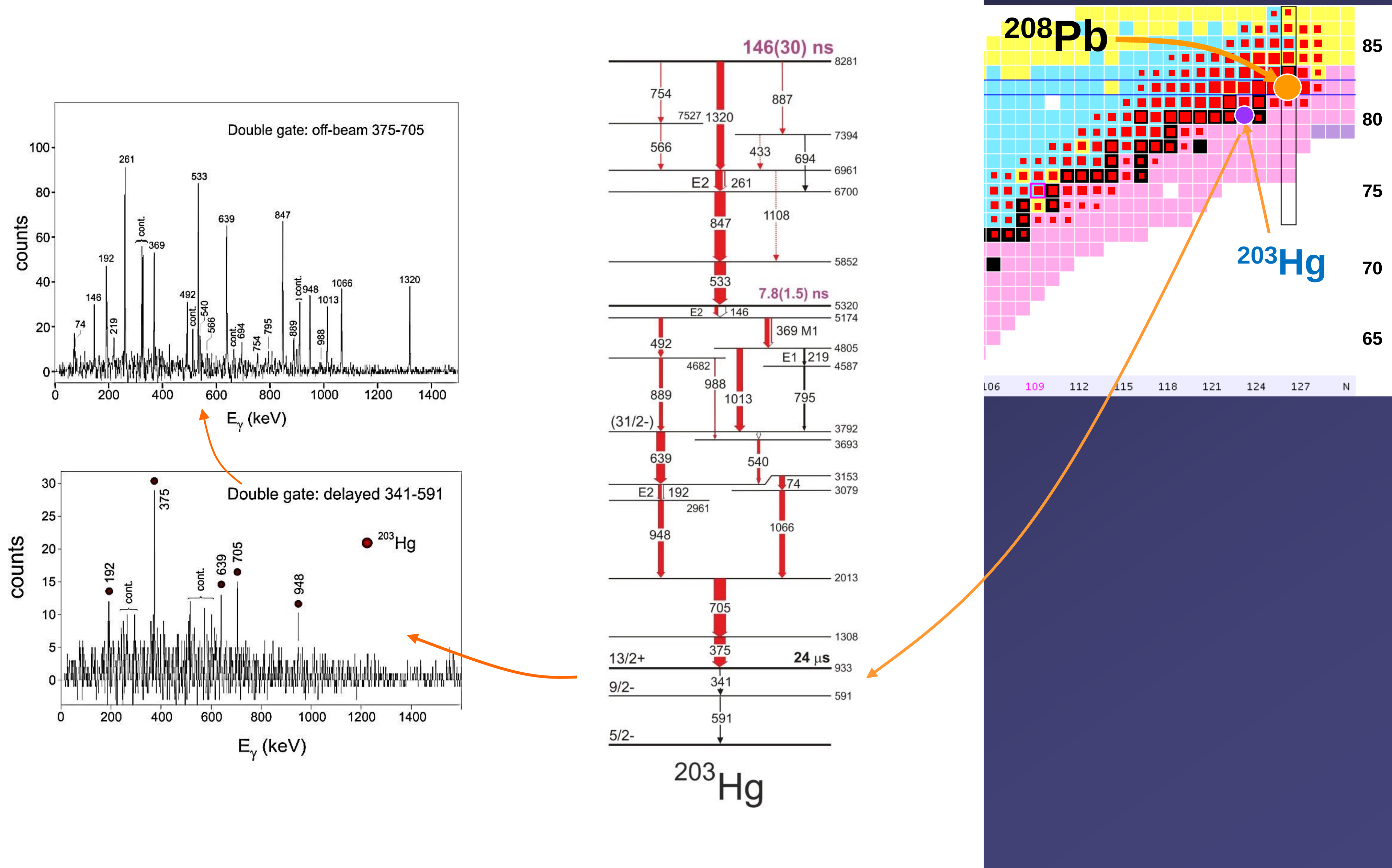






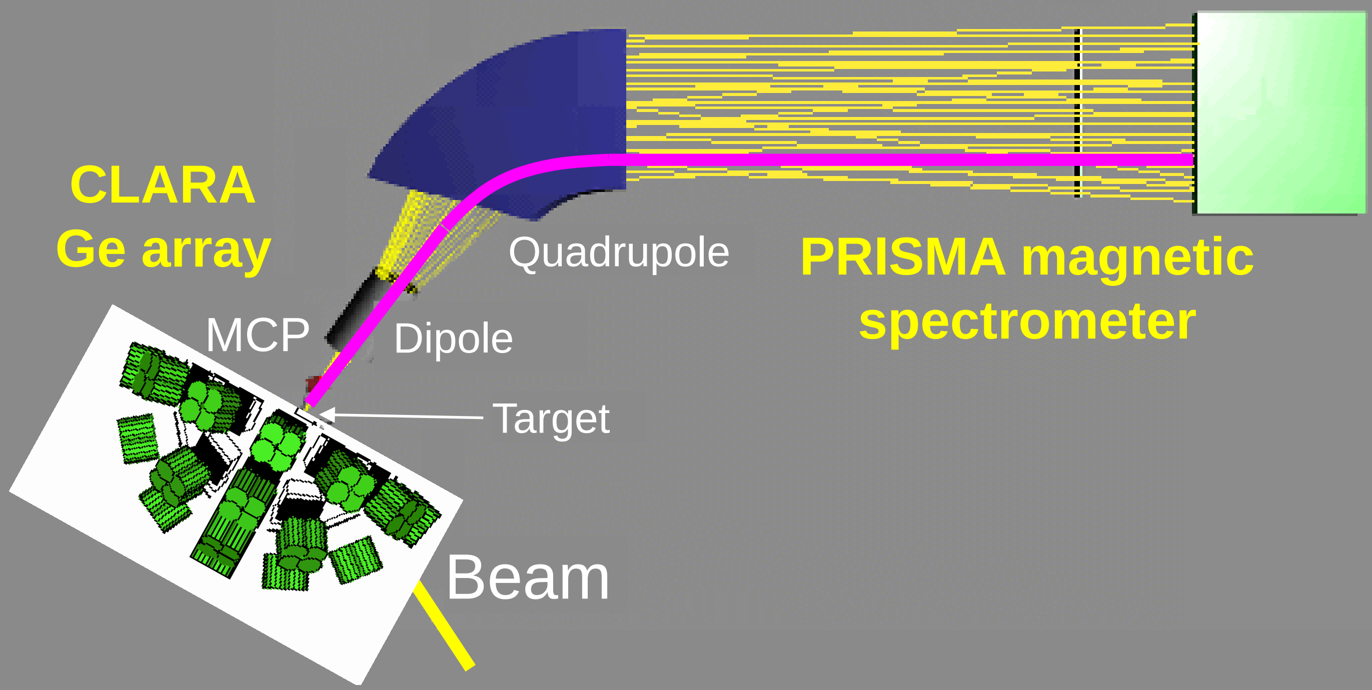
W. Krolas et al., Nucl. Phys. A724, (2003)

Example of the construction of a level scheme by using the γ–γ–γ coincidence thick-target technique



Measuring gamma rays from deep-inelastic reaction products by using magnetic spectrometers coupled to germanium arrays

CLARA+PRISMA detection system at LNL, Legnaro



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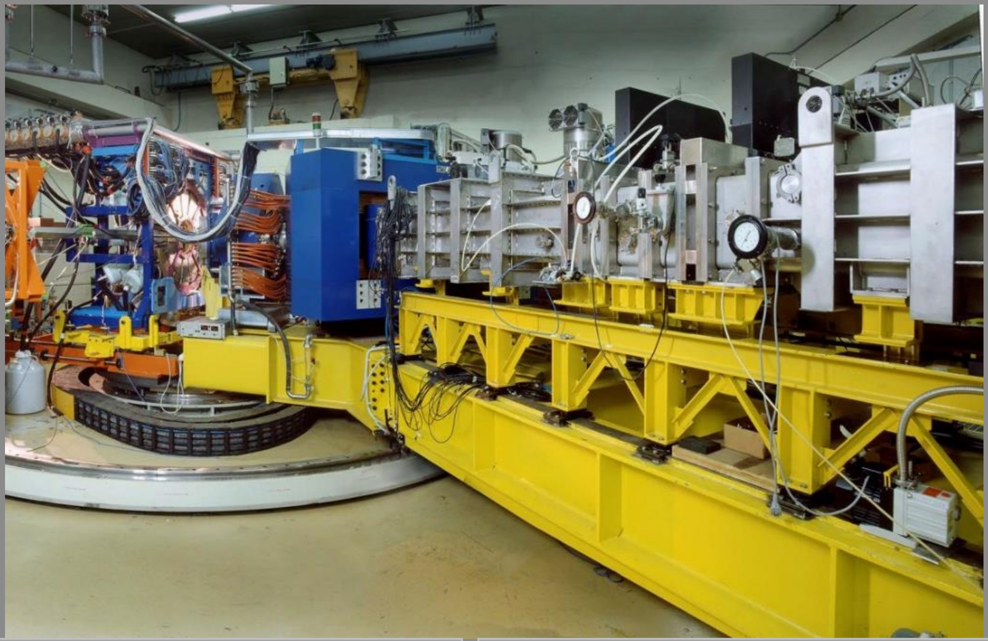


🗐 A. M. Stefanini et al., Nucl. Phys. A701, 217c (2002)

🗐 A. Gadea et al., Eur. Phys. J. A 20, 193 (2004).

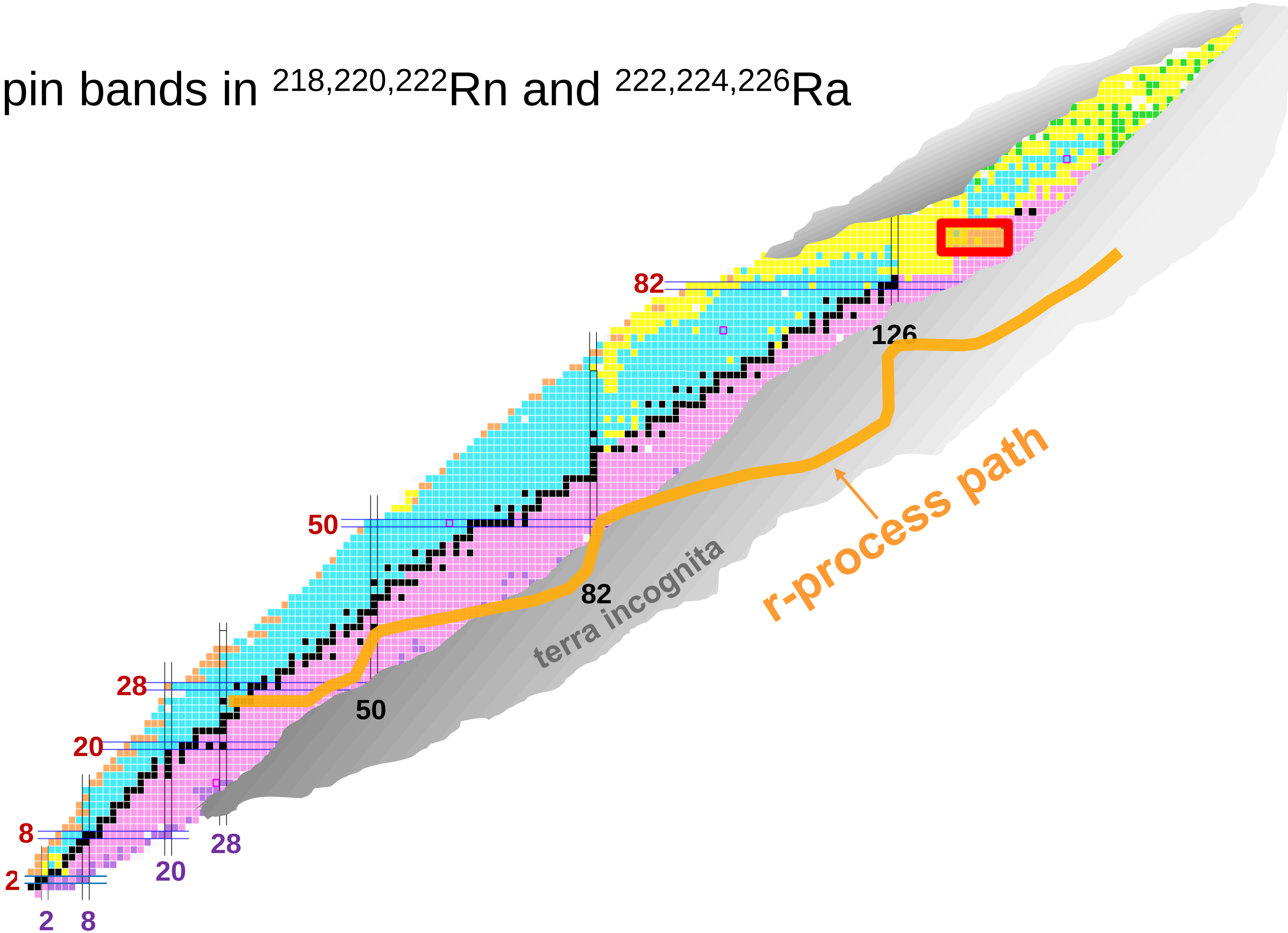
Large-acceptance spectrometer VAMOS coupled to EXOGAM Ge array (at present to AGATA) at GANIL, Caen (France)

🗐 H. Savajols, Nucl. Instr. and Meth. B 204 (2003) 146

We have the method that enables the studies of high-spin structures in neutron-rich nuclei – it relies on using deep-inelastic processes and two detection techniques:

a) thick-target technique with large germanium arrays
or
b) thin target technique with magnetic spectrometers coupled to germanium arrays.

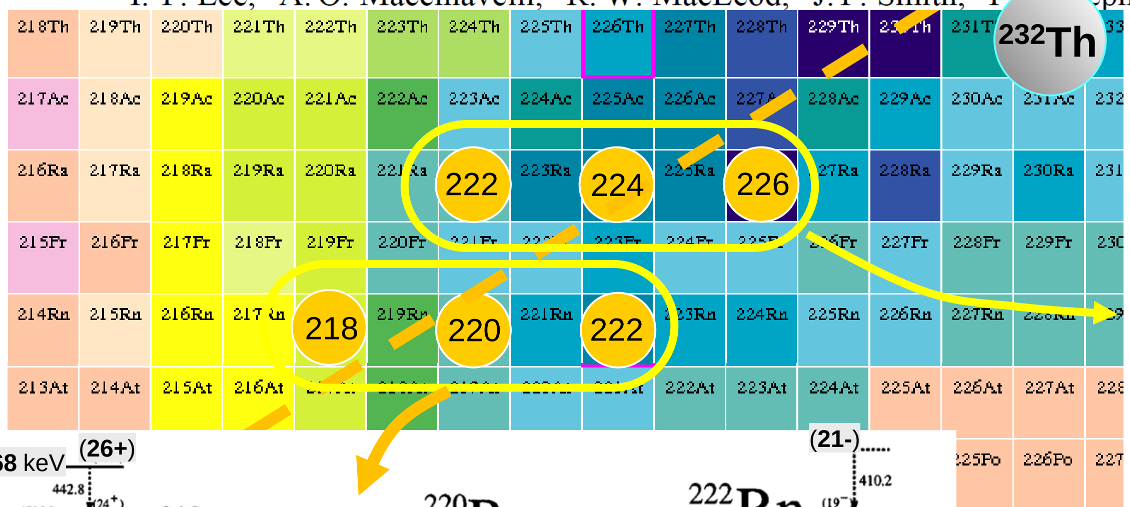
High-spin bands in ^{218,220,222}Rn and ^{222,224,226}Ra

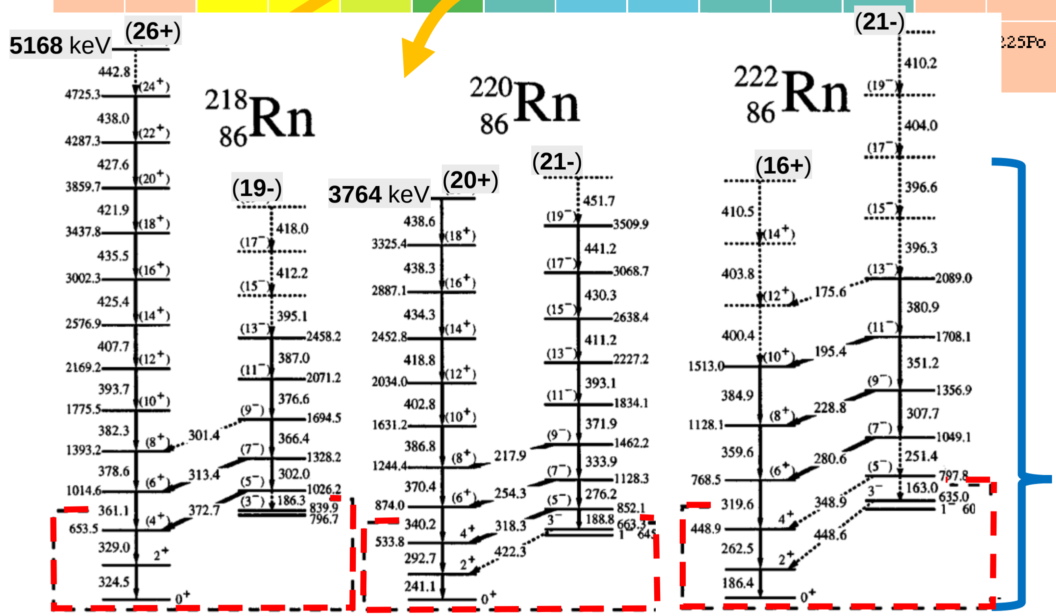


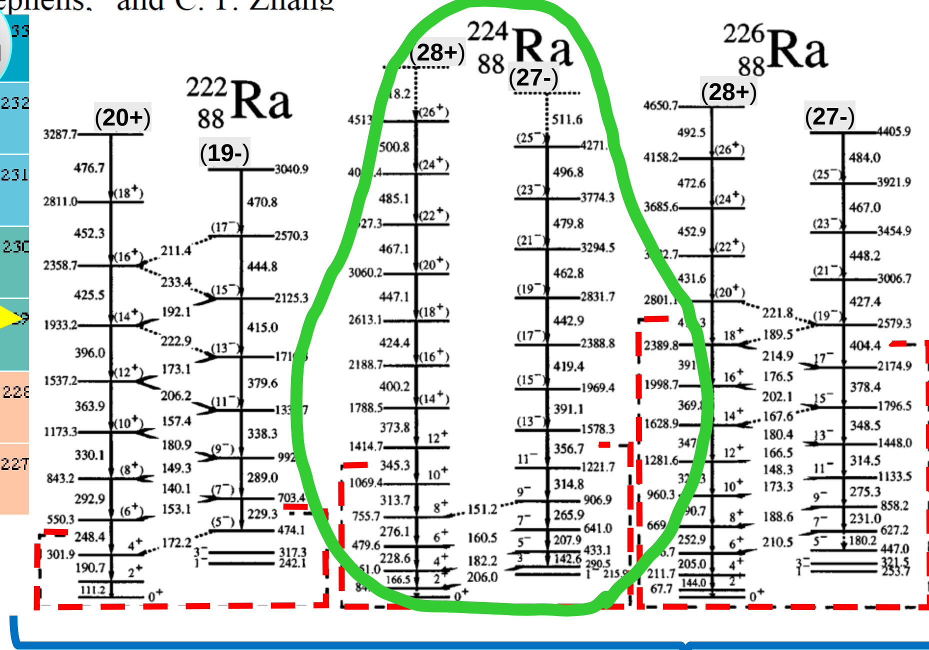
Observation of Octupole Structures in Radon and Radium Isotopes and Their Contrasting Behavior at High Spin

J. F. C. Cocks,[1] P. A. Butler,[1] K. J. Cann,[1] P. T. Greenlees,[1] G. D. Jones,[1] S. Asztalos,[2] P. Bhatta
R. M. Clark,[2] M. A. Deleplanque,[2] R. M. Diamond,[2] P. Fallon,[2] B. Fornal,[4] P. M. Jones,[5] R. Ju
I. Y. Lee,[2] A. O. Macchiavelli,[2] R. W. MacLeod,[2] J. F. Smith,[7] F. S. Stephens,[2] and C. T. Zhang[3]

L. P. Gaffney, P. A. Butler *et al.*, NATURE 497, (2013)



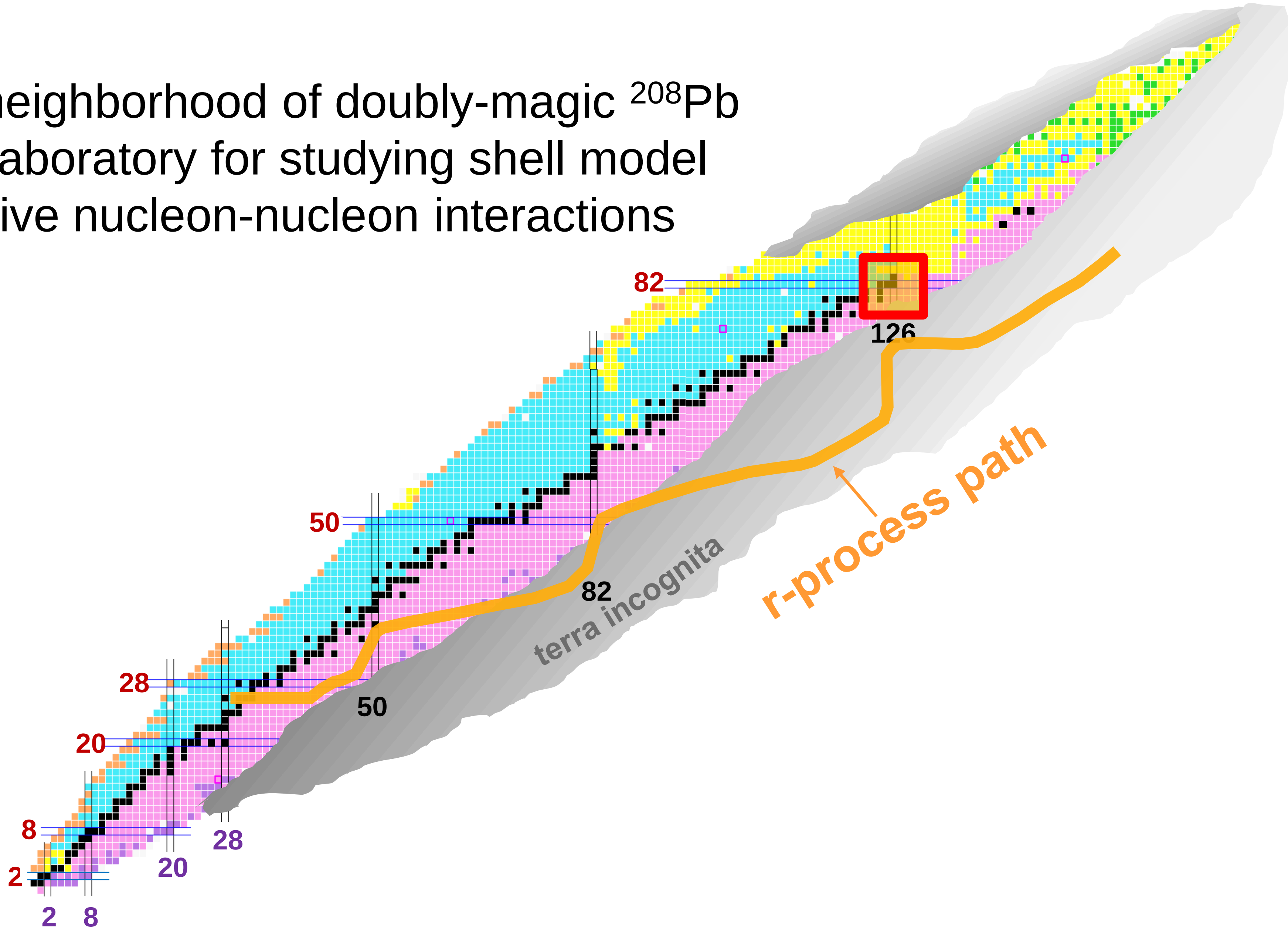




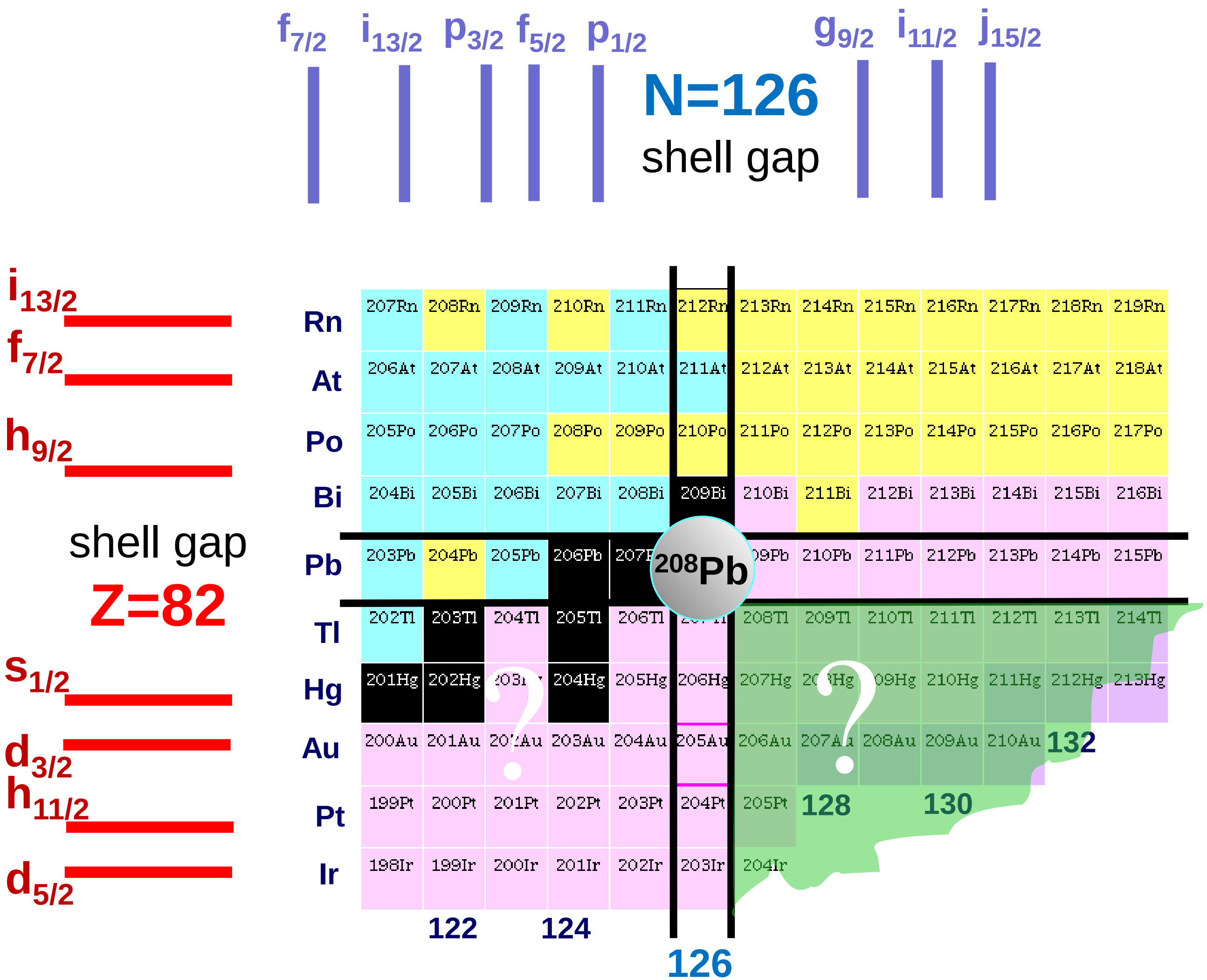
Radon isotopes behave like <u>octupole vibrators</u>

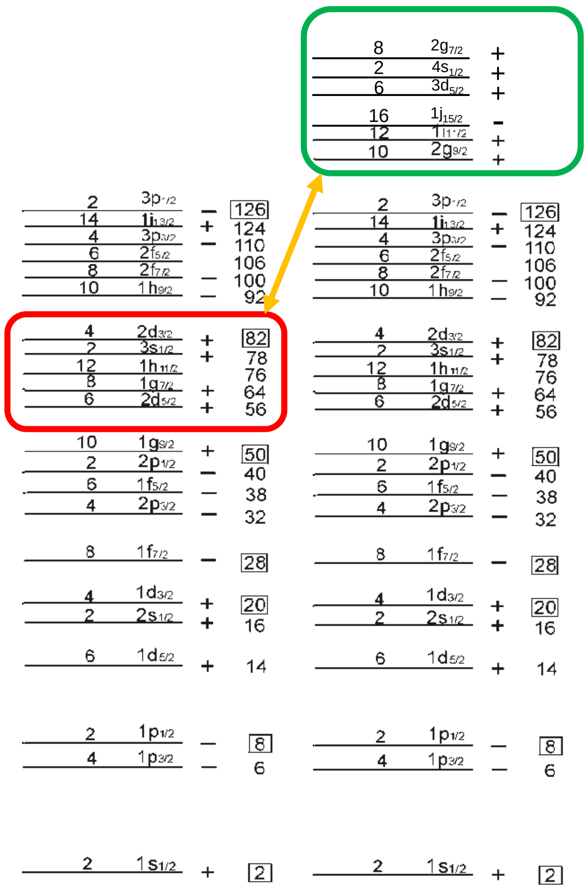
Radium isotopes behave like nuclei having <u>stable octupole deformation</u>

The neighborhood of doubly-magic ^{208}Pb as a laboratory for studying shell model effective nucleon-nucleon interactions

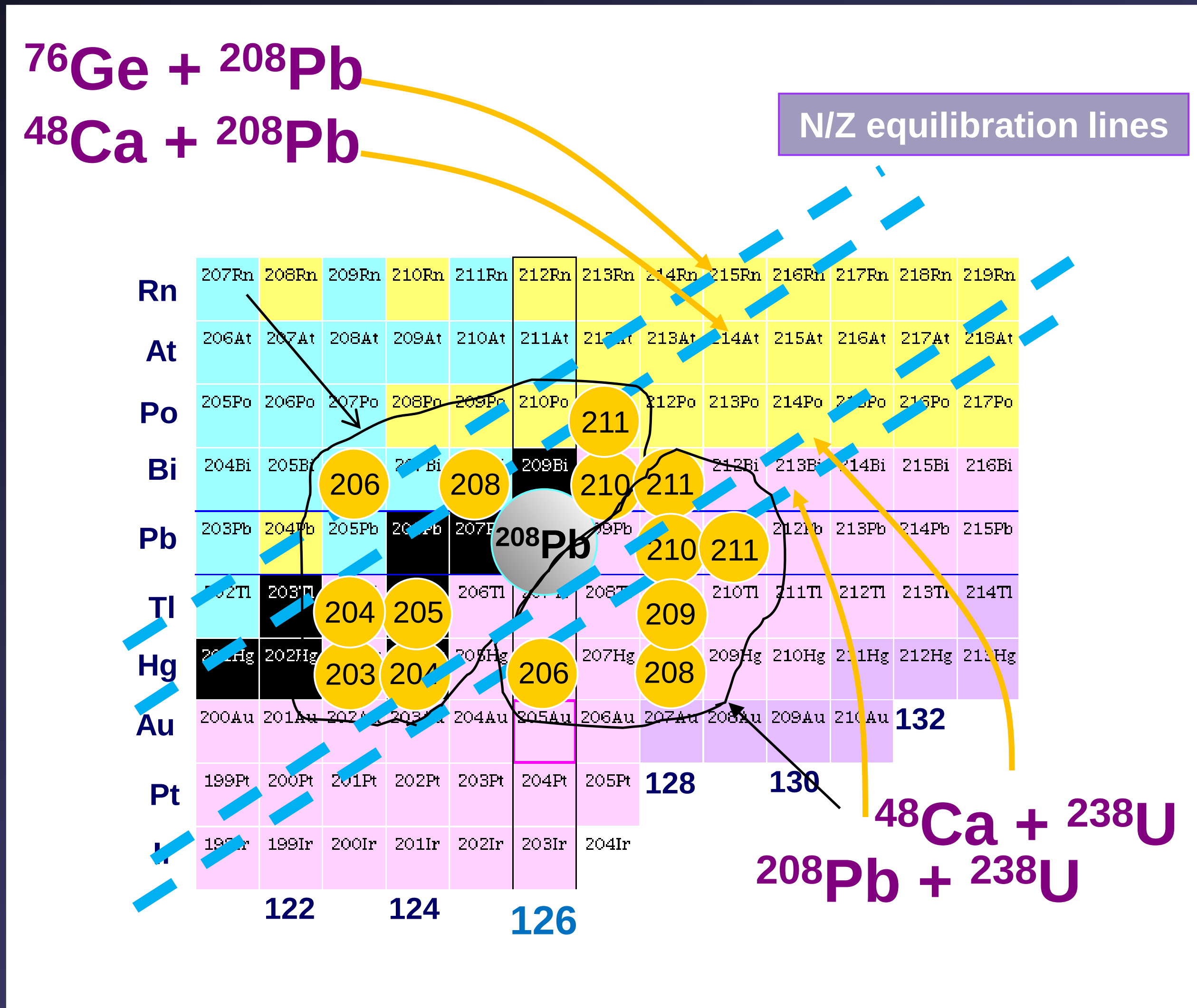


Proton and neutron single particle orbitals

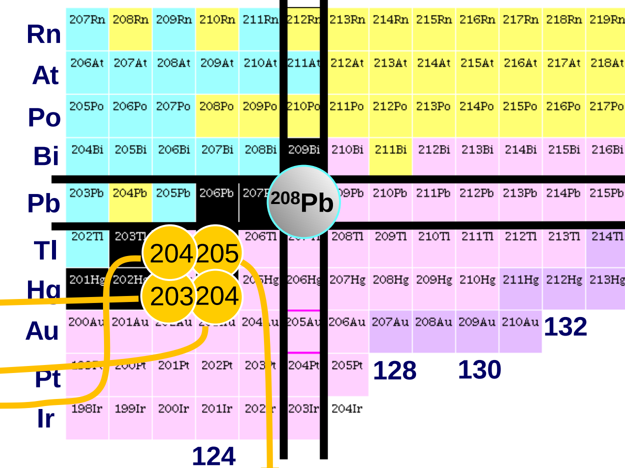


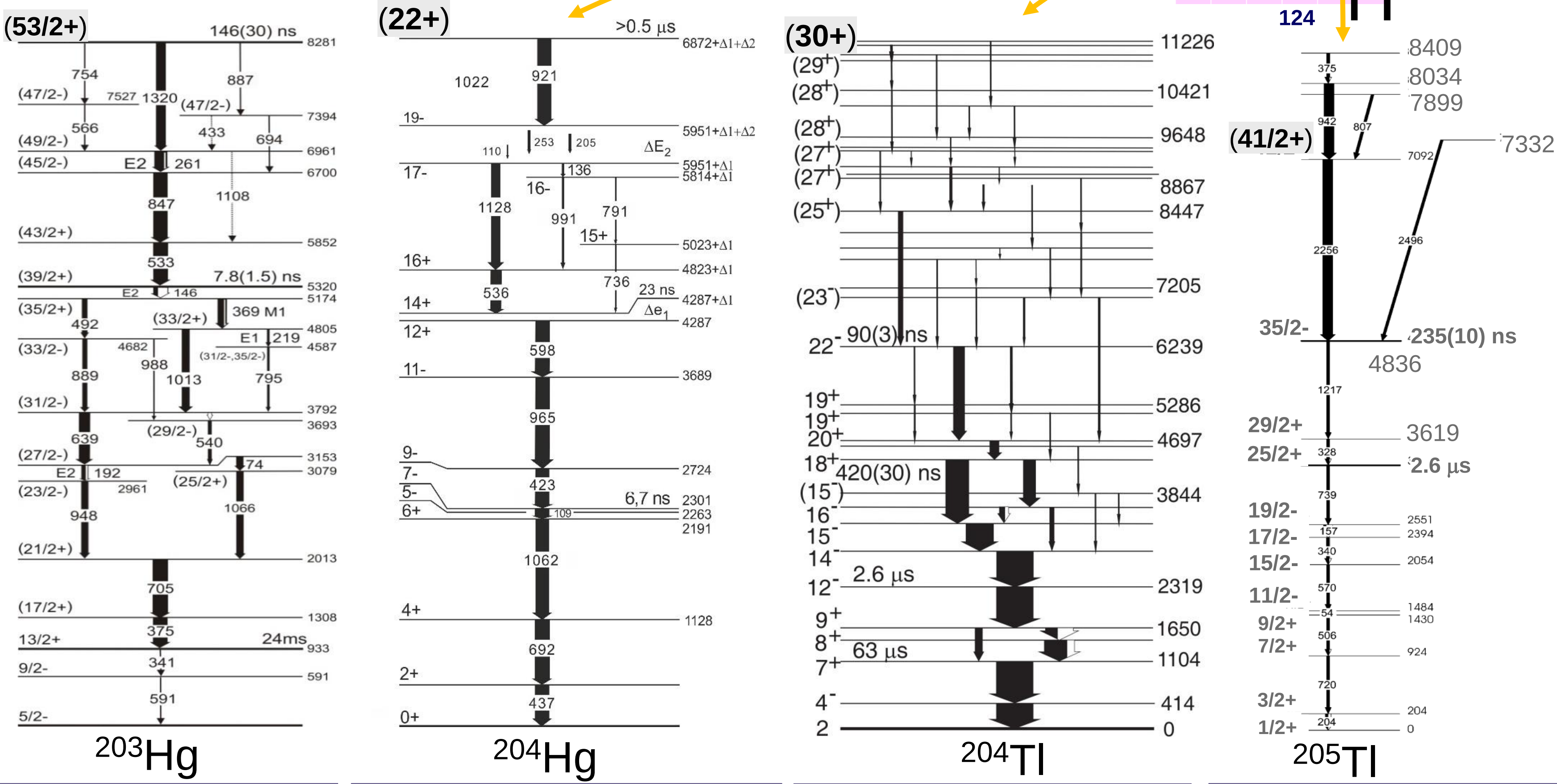


Investigations in the region of doubly-magic ^{208}Pb by employing deep-inelastic reactions and the γ–γ–γ coincidence thick-target technique (with GAMMASPHERE at ANL)



Identification of high-spin structures in nuclei located „south-west”of ^{208}Pb from the γ–γ–γ coincidence thick-target experiments (GAMMASPHERE at ANL)





B. Szpak et al., PRC 83, 064315 (2011)

J. Wrzesinski, G. Lane et al., subm. to PRC

R. Broda et al., PRC 84, 014330 (2011)

J. Wrzesinski et al., Eur. Phys. J 20 (2004)

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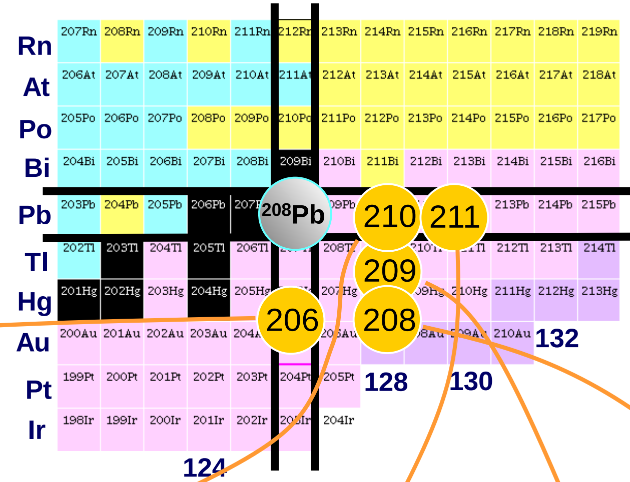
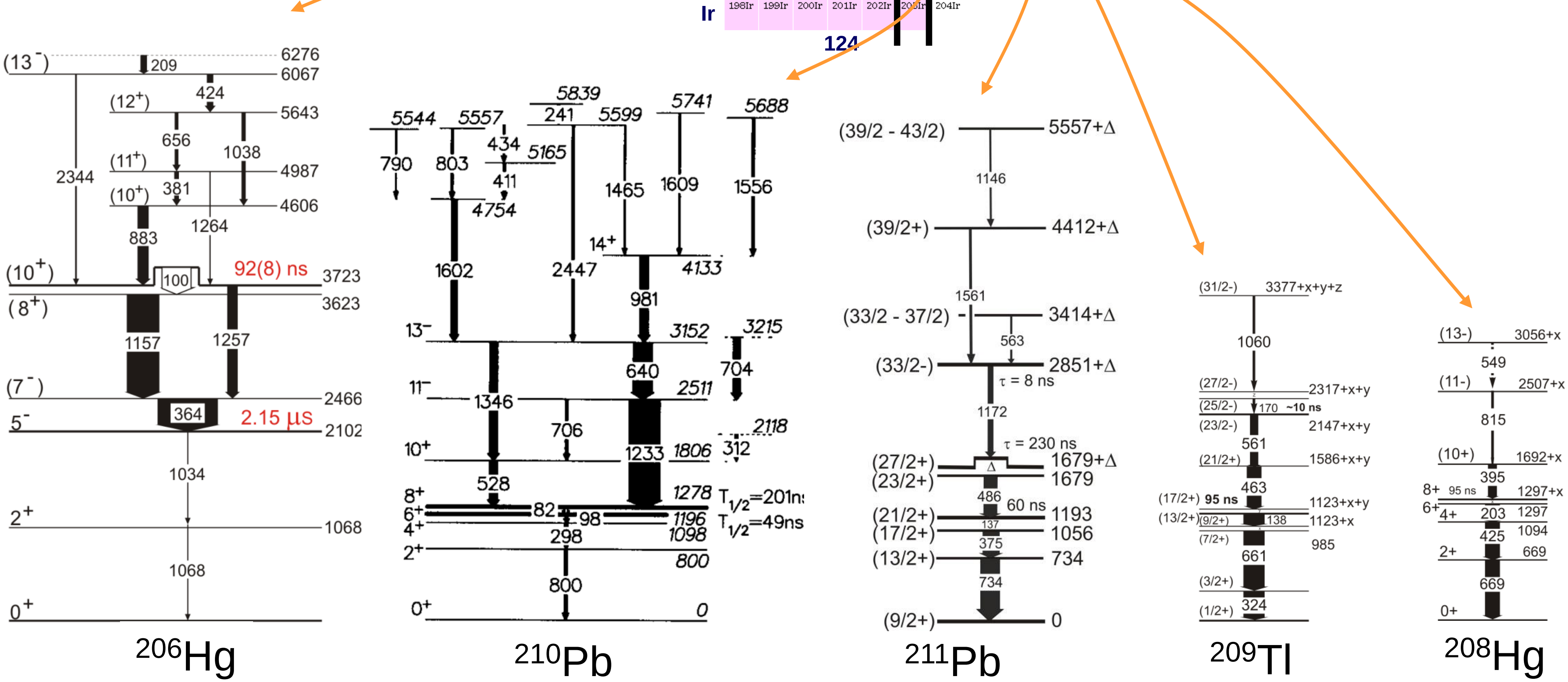




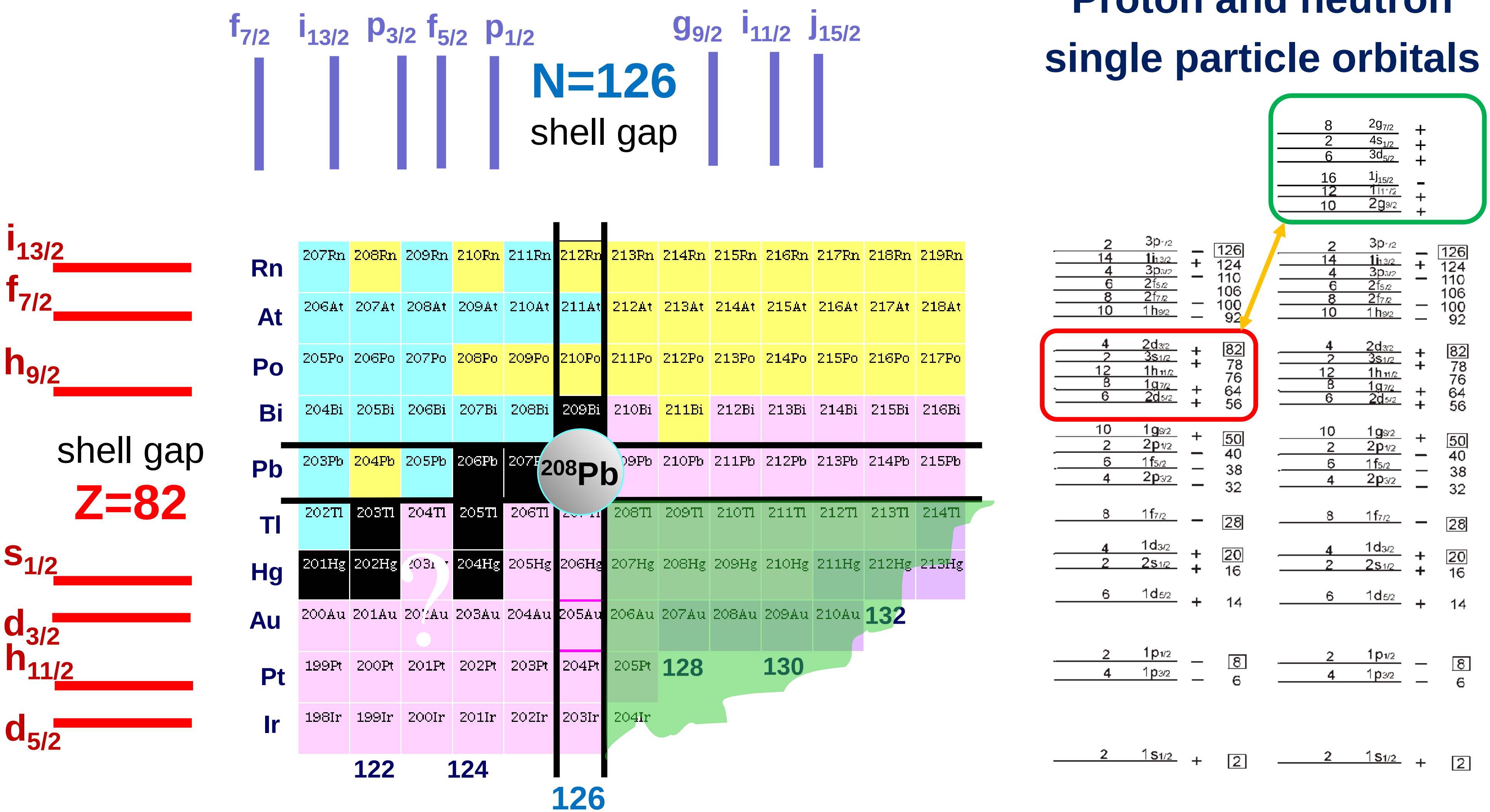
B. F. et al., Phys. Rev. Lett. 87 (2001)

G. Lane et al., Nucl. Phys. A682 (2001)

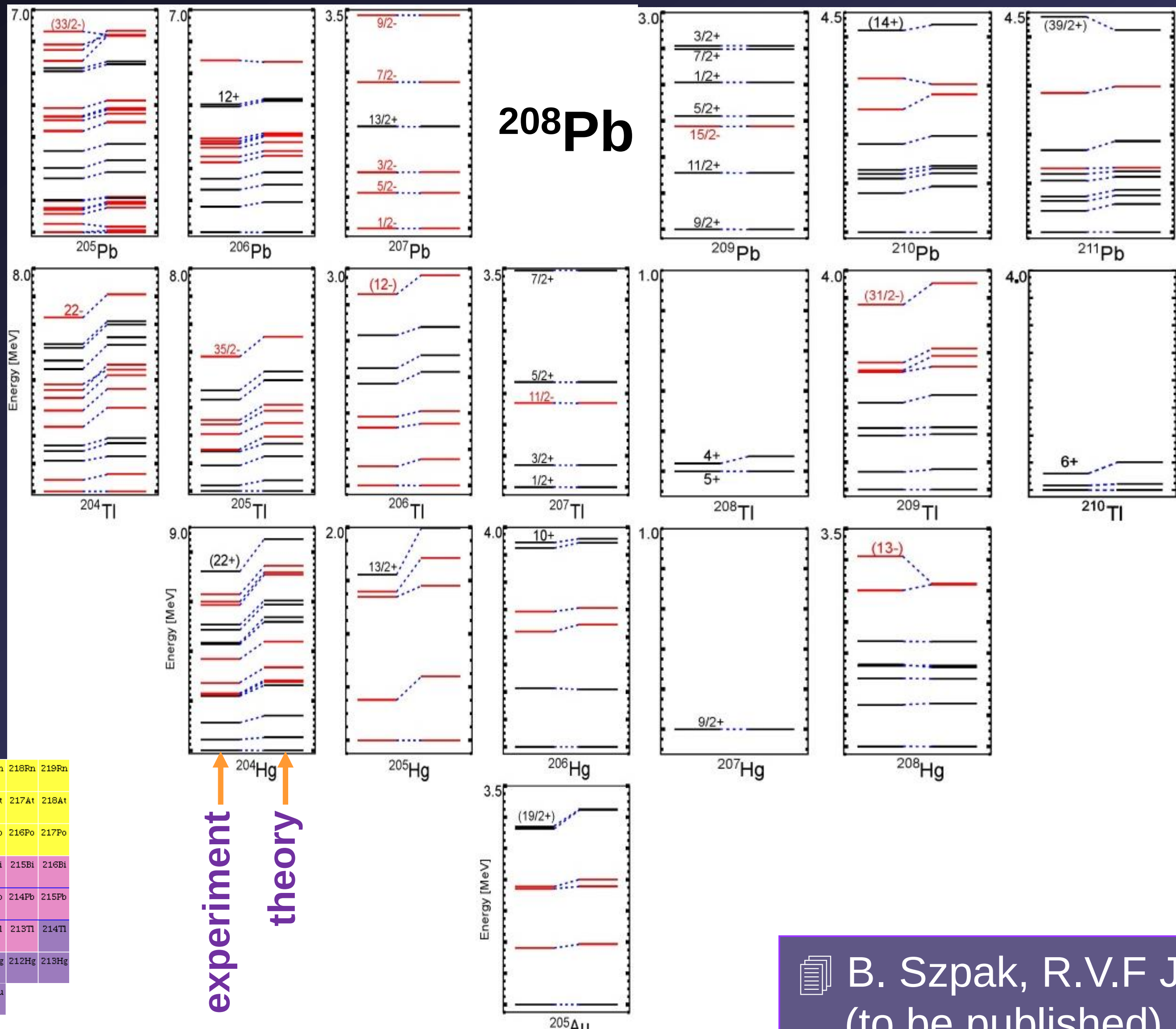
G. Lane et al., Phys. Lett. B 606 (2005)

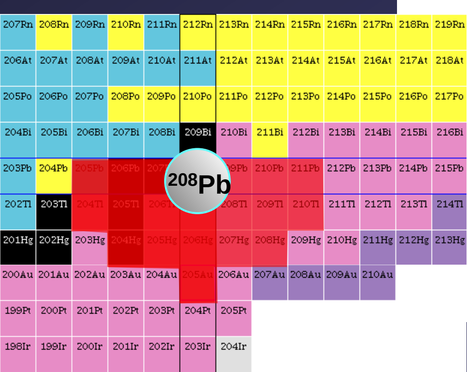
B. F. et al., Proc. Vietri Conf. (2010)

Proton and neutron single particle orbitals

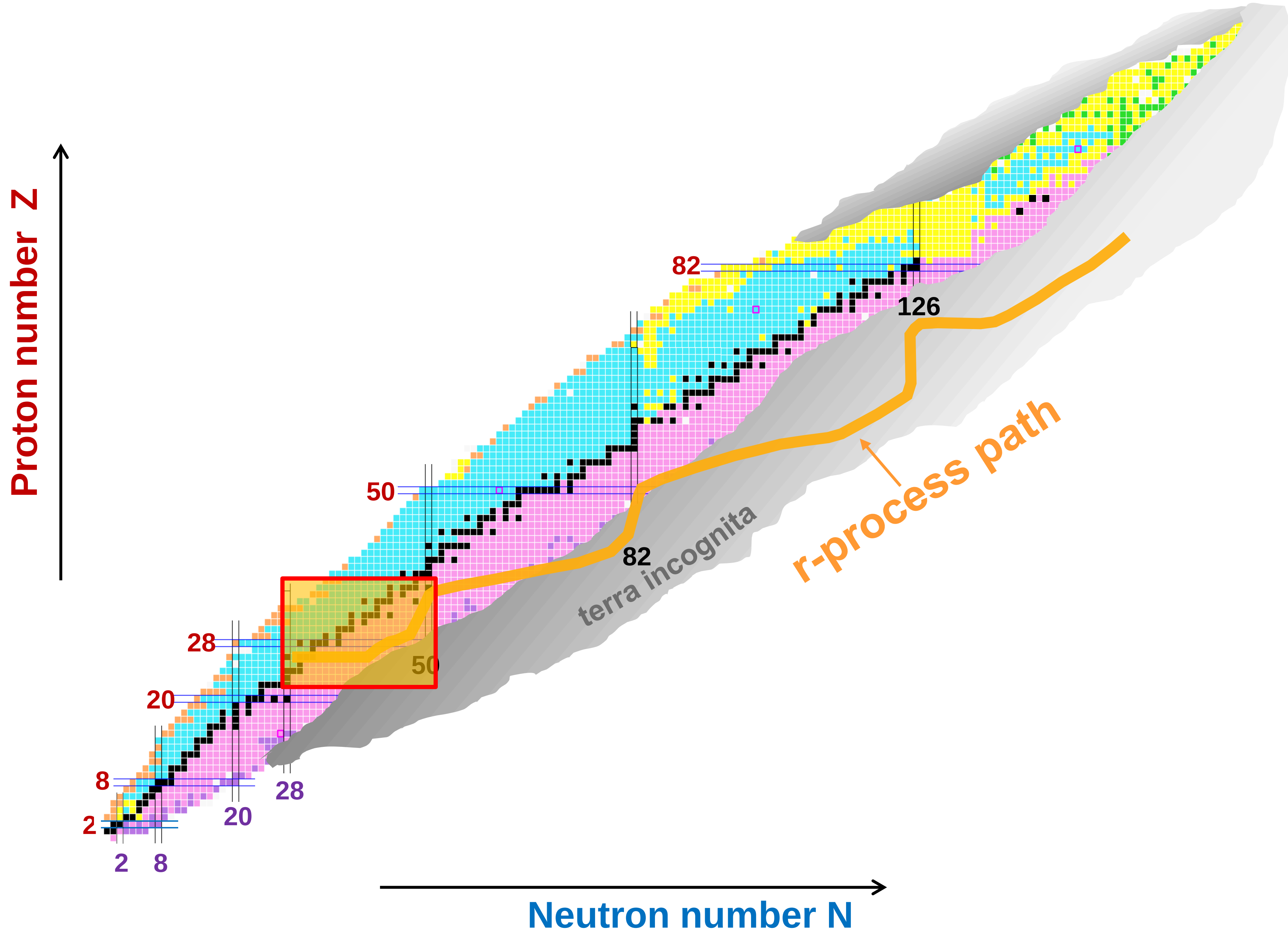


High-spin structures SOUTH of doubly-magic ^{208}Pb - comparison with shell-model calculations using the realistic V_{low-k} interaction (computer codes CENS and OXBASH).



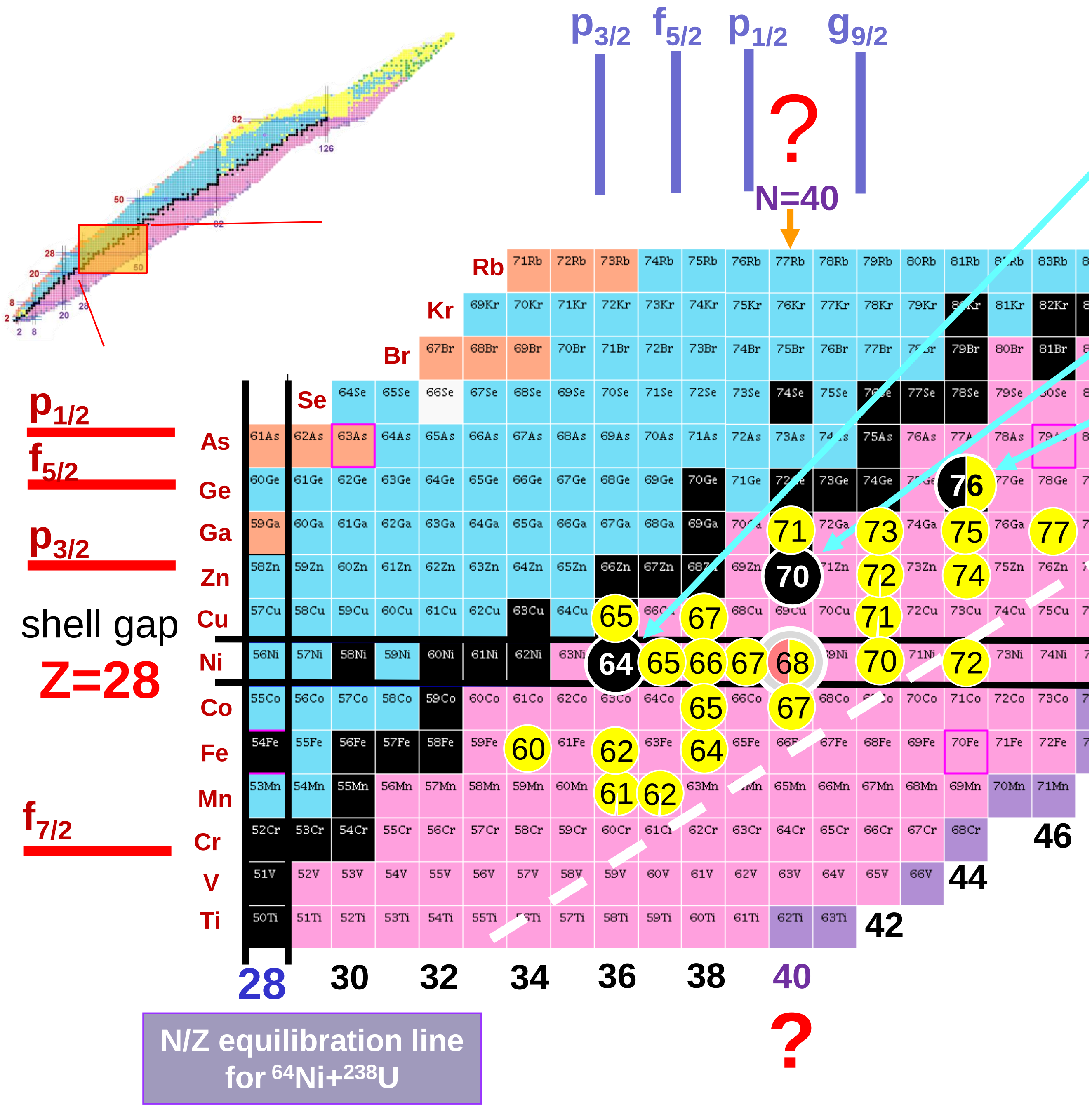


B. Szpak, R.V.F Janssens, B.F., (to be published)



Proton number Z
Neutron number N
82
50
28
20
8
2
2
8
20
28
50
82
126
terra incognita
r-process path

Does there exist a sizable energy gap at N = 40 in neutron-rich nuclei?



GASP (thick target)
R. Broda et al., PRL 74, 868 (1995)

GAMMASPHERE (thick target)
N. Hotelink et al., PRC 74, 064313 (2006)
N. Hotelink et al., PRC 77, 044314 (2008)
I. Stefanescu et al., PRC C 79, 064302 (2009)
C.J. Chiara et al., PRC 82, 054313 (2010)
N. Hotelinket al., PRC 82, 044305 (2010)
C.J. Chiara et al., PRC 84, 037304 (2011)
C.J. Chiara et al., PRC 85, 024309 (2012)
C.J. Chiara et al., PRC 86, 041304 (2012)
S. Zhu et al., PRC 85, 034336 (2012)
C.J. Chiara et al., PRC C 86, 041304 (2012)
R. Broda at al., PRC 86, 064312 (2012)

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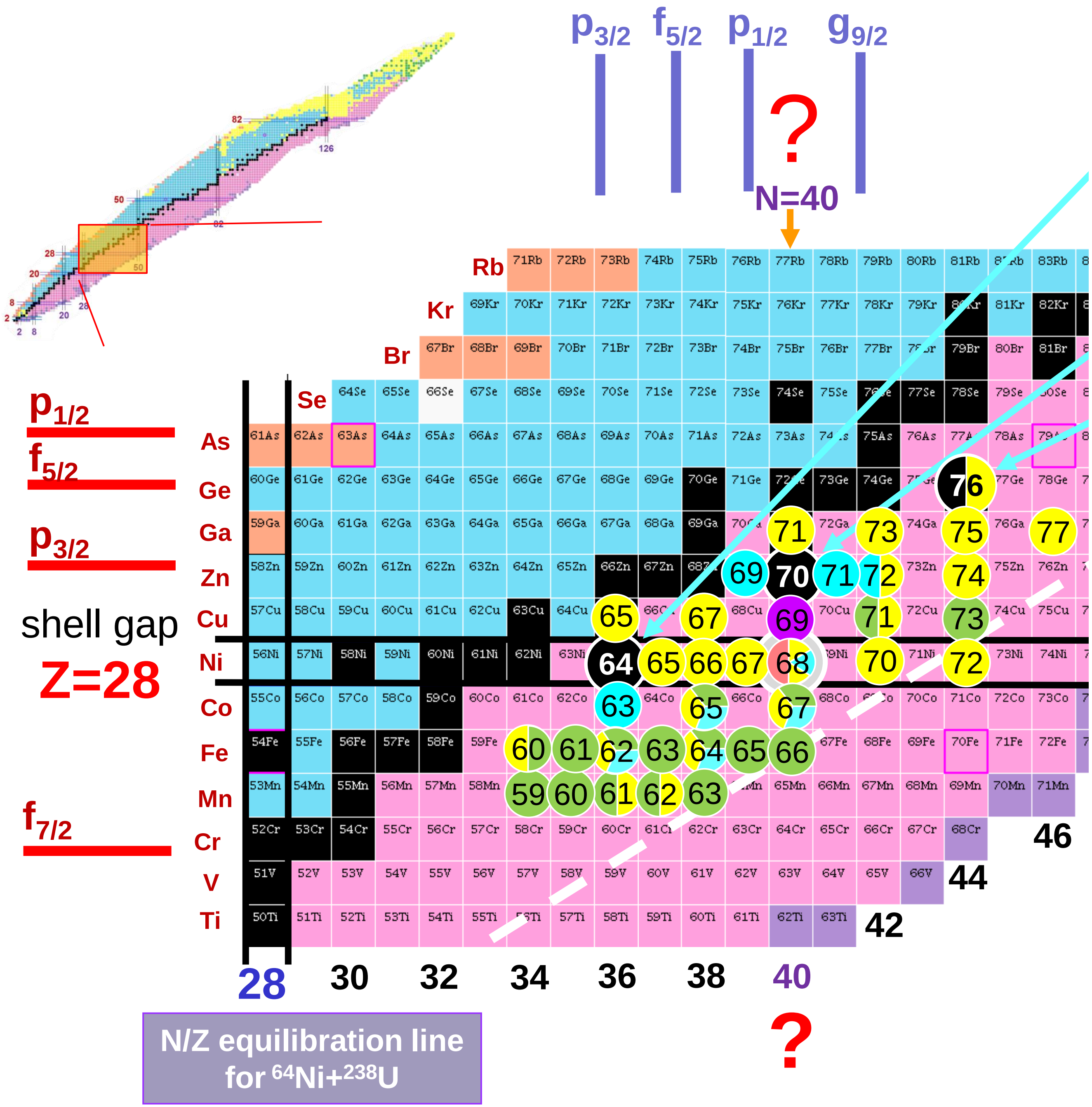

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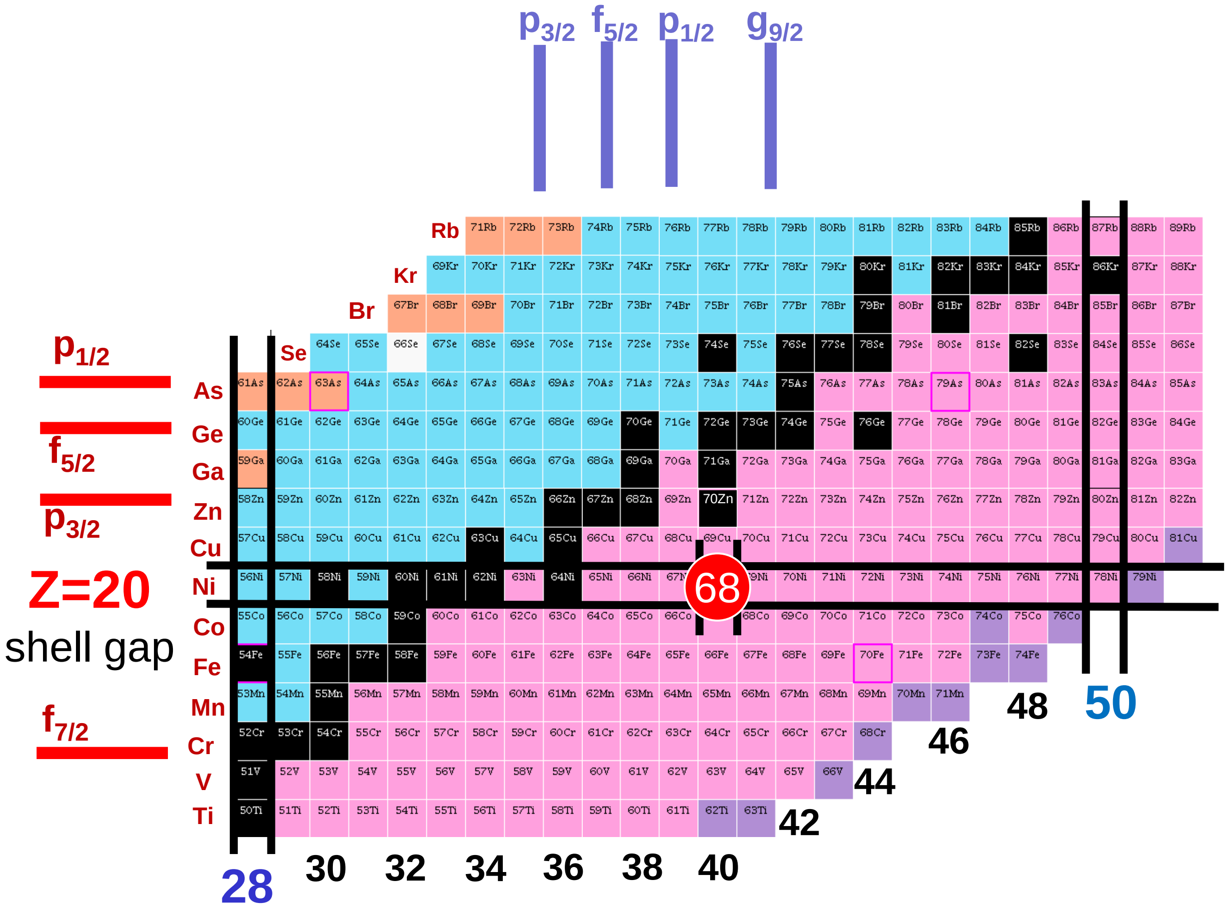
C.J. Chiara et al., PRC 82, 054313 (2010)
N. Hotelinket al., PRC 82, 044305 (2010)
C.J. Chiara et al., PRC 84, 037304 (2011)
C.J. Chiara et al., PRC 85, 024309 (2012)
C.J. Chiara et al., PRC 86, 041304 (2012)
S. Zhu et al., PRC 85, 034336 (2012)
C.J. Chiara et al., PRC C 86, 041304 (2012)
R. Broda at al., PRC 86, 064312 (2012)

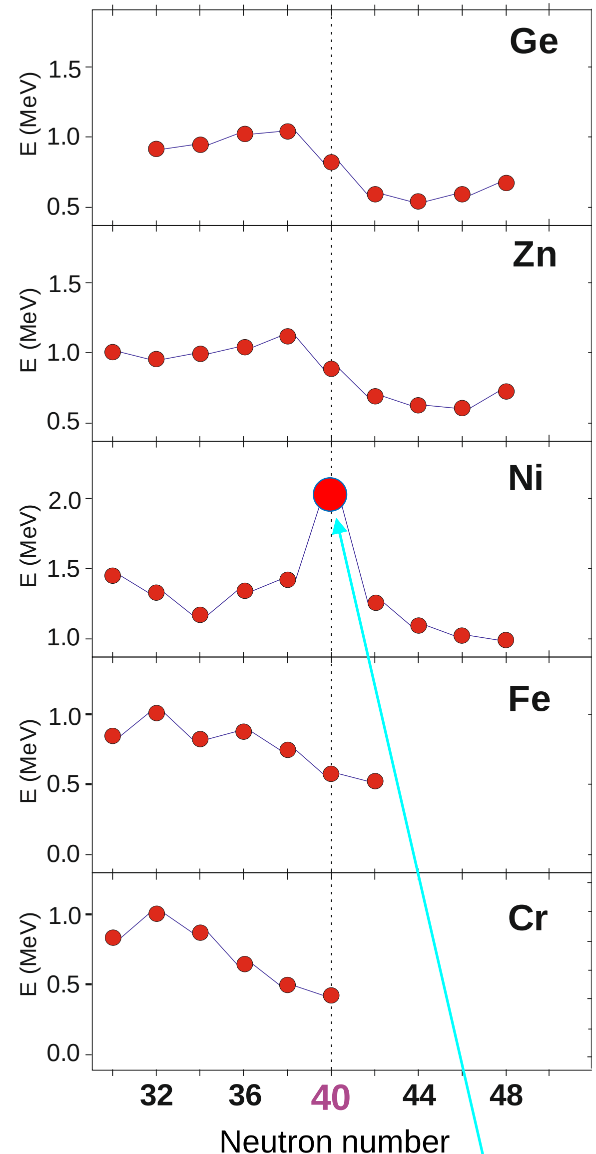
CLARA(AGATA) + PRISMA (thin taget)
S. Lunardi et al., PRC 76, 034303 (2007)
J.J. Valiente-Dobon et al., PRC 78, (2008)
F. Recchia et al., PRC 85, 064305 (2012)
M. Doncel et al., APP B44, 505 (2013)
E. Sahin at al., PRC 91, 034302 (2015)

EXOGAM+VAMOS (thin taget)
J.Ljungvall et al., PRC 81, 061301 (2010)
A. Dijon et al., PRC 83, 064321 (2011)
I. Celikovic et al., APP B44, 375 (2013)
I. Celikovic et al., PRC 91, 044311 (2015)

Isomer-scope – RIKEN (thin taget)
T.Ishi et al., NIM A 395 (1997)



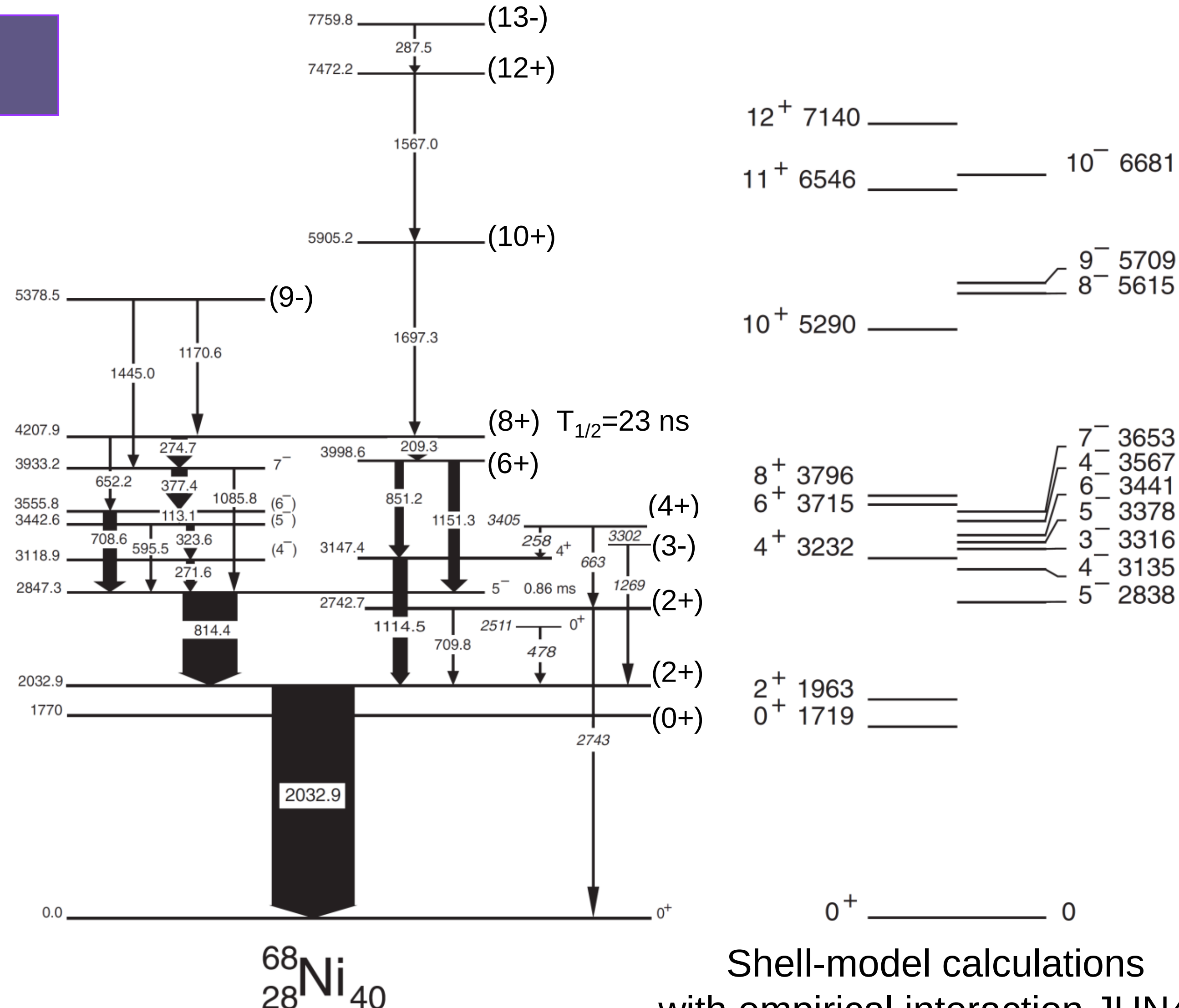
Systematics of the 2+ energy in the Cr, Fe, Ni, Zn, and Ge isotopic chains



Conclusion: The sub-shell closure at N=40 occurs in Ni nuclei, making the ^{68}Ni nucleus „almost” doubly magic.
This closure, however, is rather weak and restricted to the close proximity of ^{68}Ni.

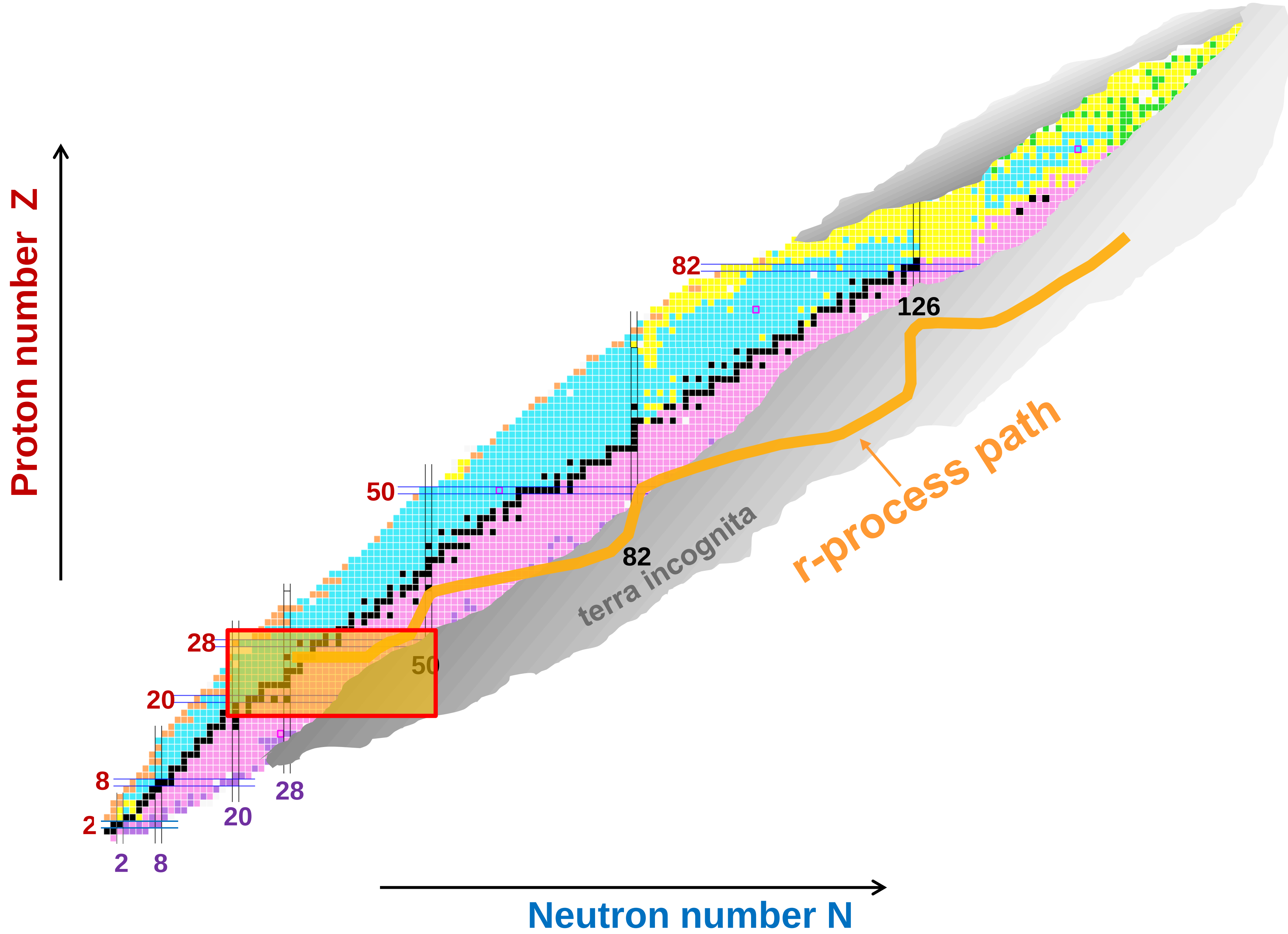
R. Broda *et al.*,
Phys. Rev. Lett. (1995)

R. Broda *et al.*,
Phys. Rev. C 86 (2012)



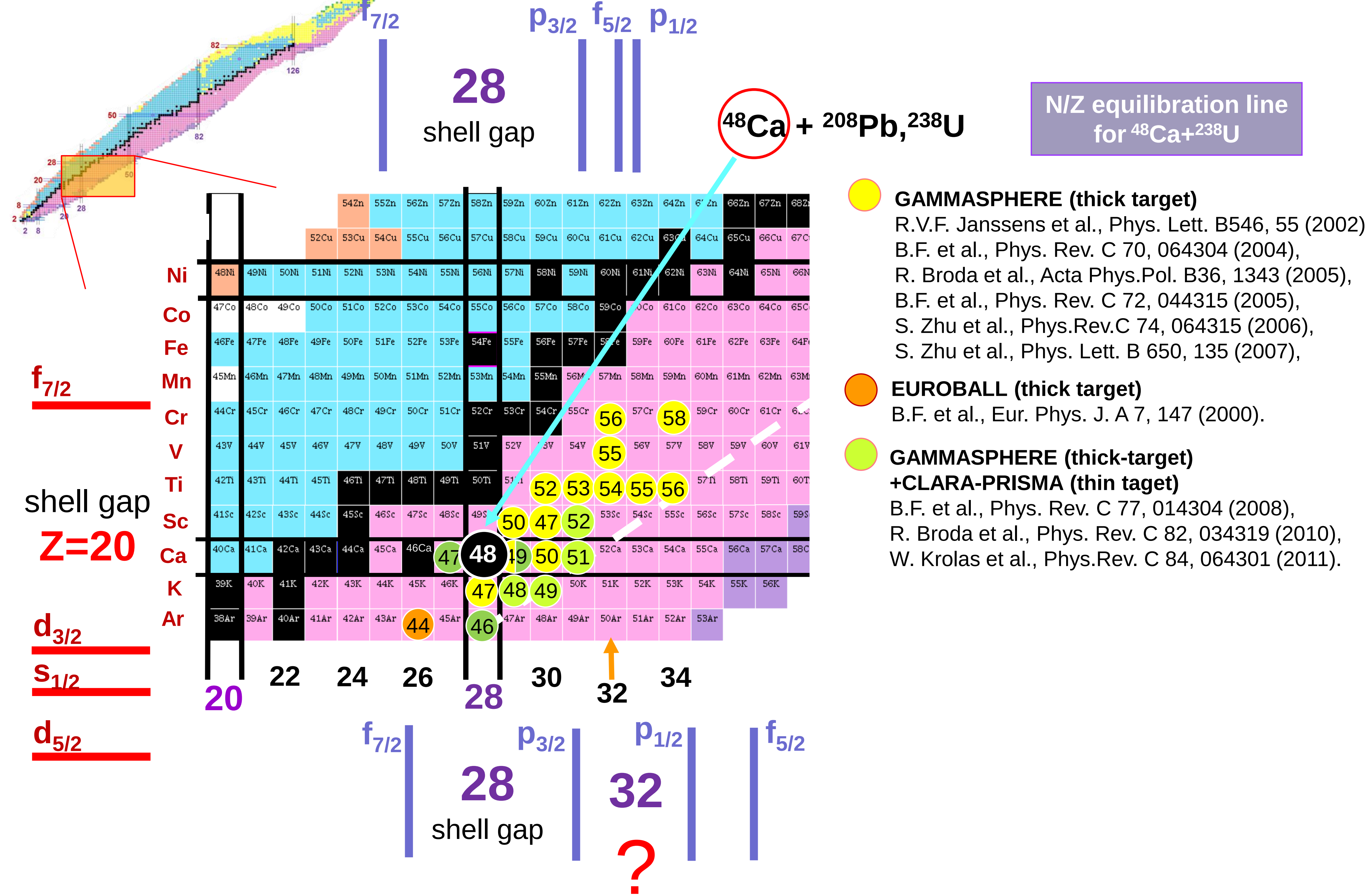
Shell-model calculations
with empirical interaction JUN45

The latest development in the ^{68}Ni yrast spectroscopy

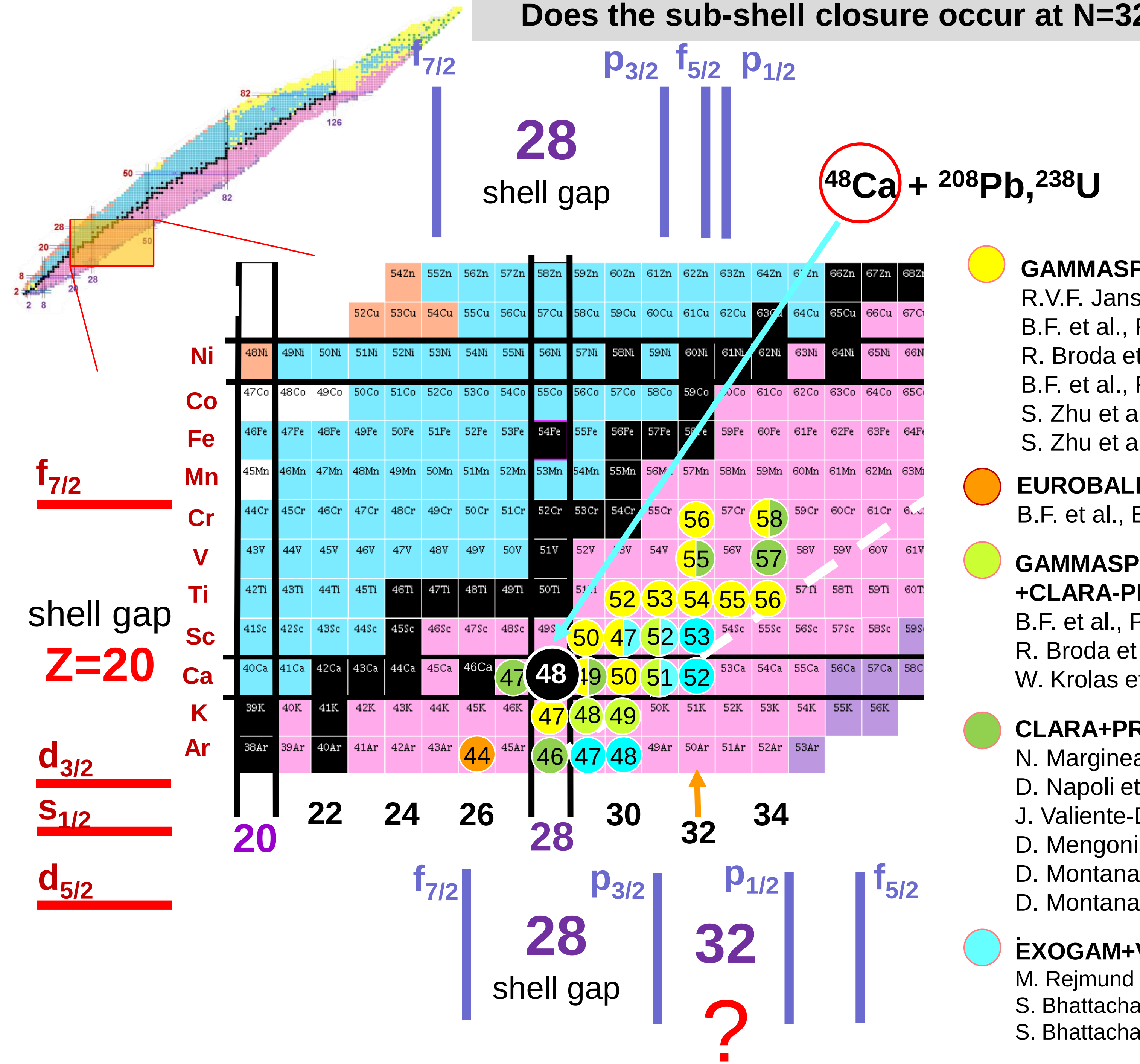


Proton number Z
Neutron number N
r-process path
terra incognita
2
8
20
28
50
82
2
8
20
28
50
82
126

Does the sub-shell closure occur at N=32 in neutron-rich nuclei?



Does the sub-shell closure occur at N=32 in neutron-rich nuclei?



N/Z equilibration line for ^{48}Ca+^{238}U

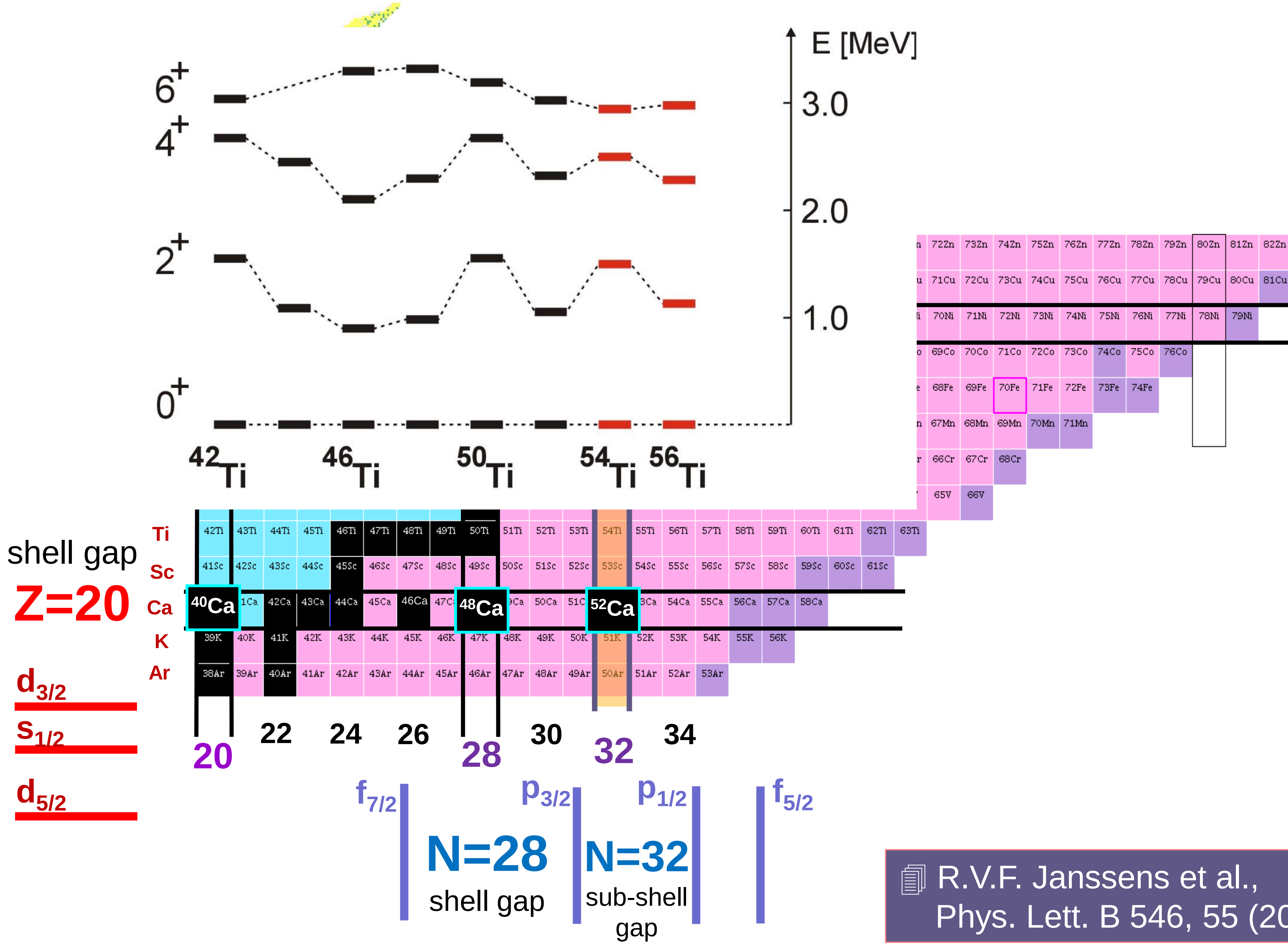
GAMMASPHERE (thick target)
R.V.F. Janssens et al., Phys. Lett. B546, 55 (2002),
B.F. et al., Phys. Rev. C 70, 064304 (2004),
R. Broda et al., Acta Phys.Pol. B36, 1343 (2005),
B.F. et al., Phys. Rev. C 72, 044315 (2005),
S. Zhu et al., Phys.Rev.C 74, 064315 (2006),
S. Zhu et al., Phys. Lett. B 650, 135 (2007),

EUROBALL (thick target)
B.F. et al., Eur. Phys. J. A 7, 147 (2000).

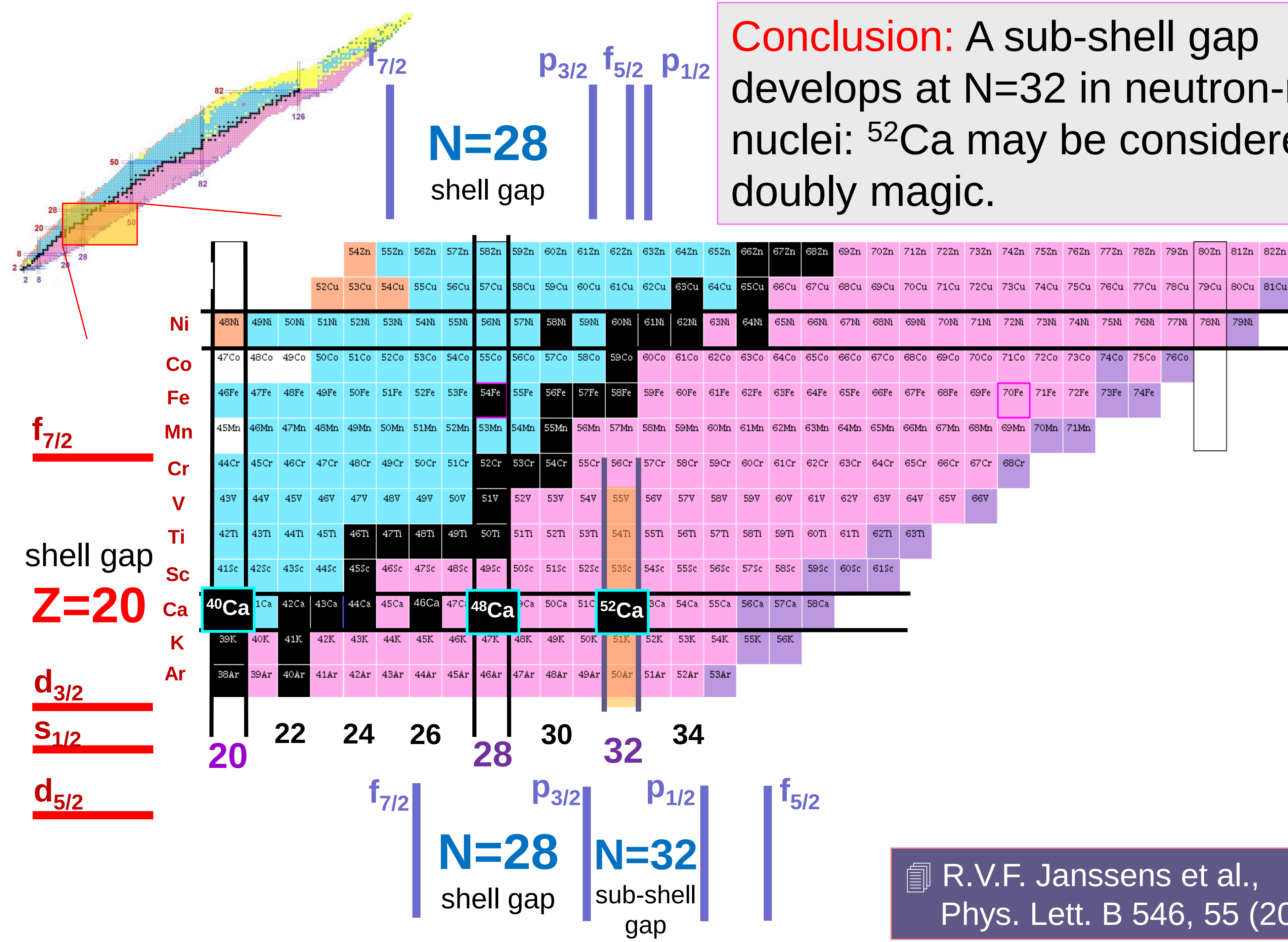
GAMMASPHERE (thick-target) +CLARA-PRISMA (thin taget)
B.F. et al., Phys. Rev. C 77, 014304 (2008),
R. Broda et al., Phys. Rev. C 82, 034319 (2010),
W. Krolas et al., Phys.Rev. C 84, 064301 (2011).

CLARA+PRISMA (thin taget)
N. Marginean et al., Phys. Lett. B 633, 696 (2006),
D. Napoli et al., J. Phys.: Conf. Ser. 49, 91 (2006),
J. Valiente-Dobon et al., PRL. 102, 242502 (2009),
D. Mengoni et al., Phys.Rev. C 82, 024308 (2010),
D. Montanari et al., Phys.Lett. B 697, 288 (2011),
D. Montanari et al., Phys.Rev. C 85, 044301 (2012).

EXOGAM+VAMOS (thin taget)
M. Rejmund et al., Phys. Rev. C 76, 021304(R) (2007),
S. Bhattacharyya et al., PRL 101, 032501 (2008),
S. Bhattacharyya et al., Phys.Rev. C 79, 014313 (2009)



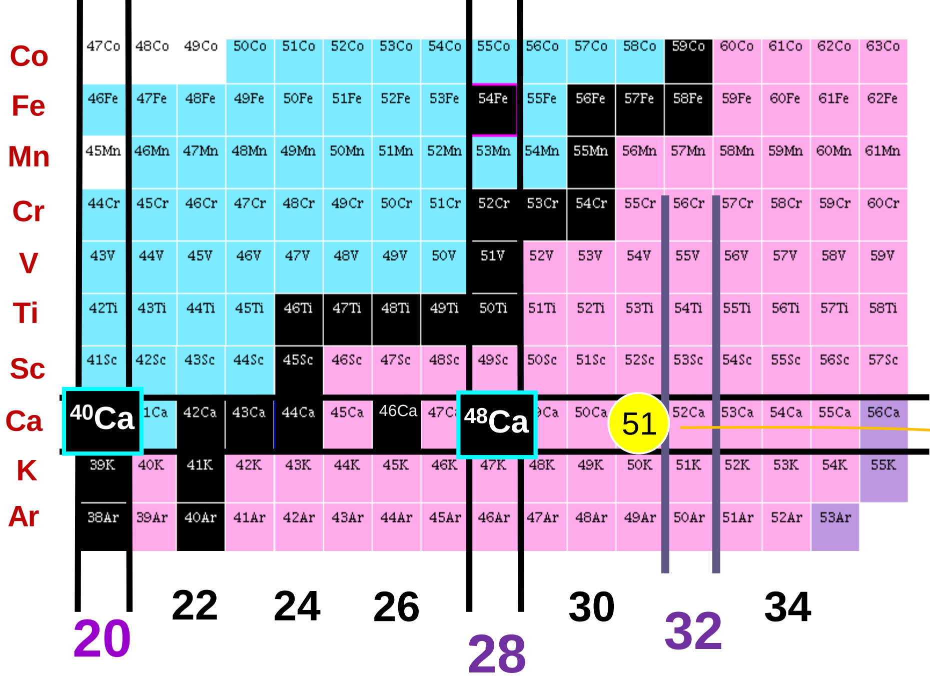
R.V.F. Janssens et al., Phys. Lett. B 546, 55 (2002).

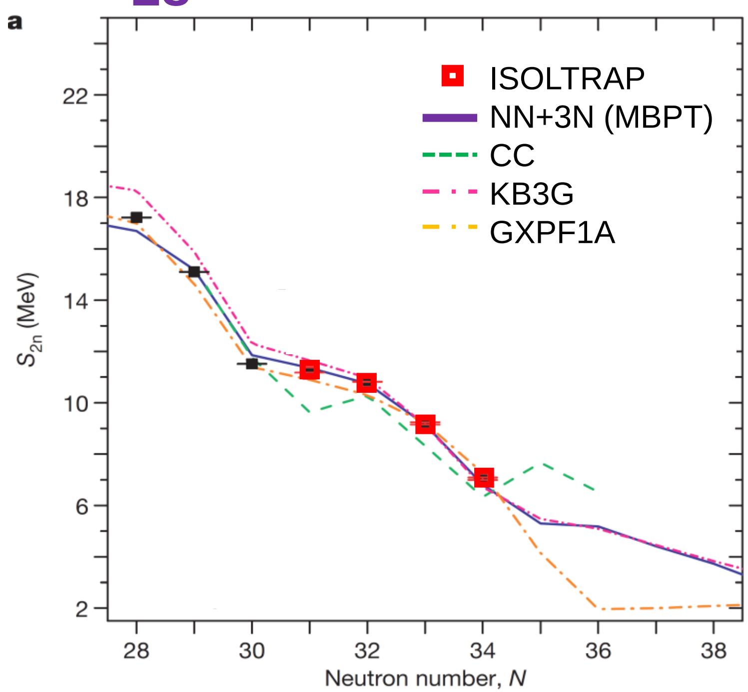


Conclusion: A sub-shell gap develops at N=32 in neutron-rich nuclei: ^{52}Ca may be considered doubly magic.

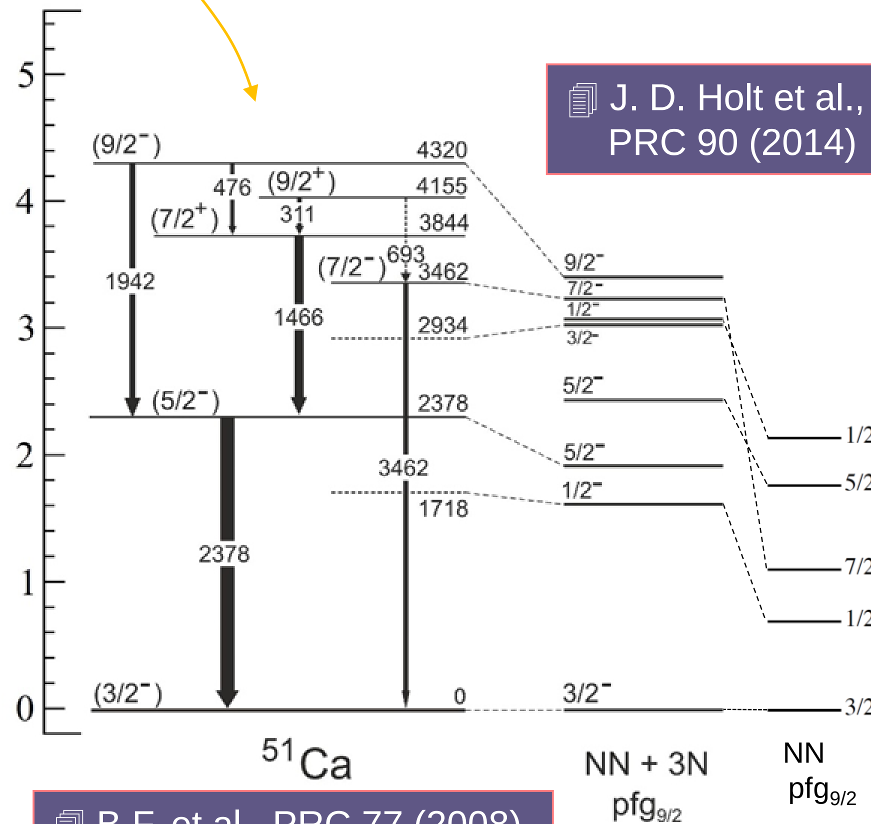
R.V.F. Janssens et al., Phys. Lett. B 546, 55 (2002).

Valence-shell many-body perturbation theory (MBPT) calculations based on chiral two- and three-nucleon interactions (NN+3N).





F. Wienholtz et al., NATURE 498 (2013)

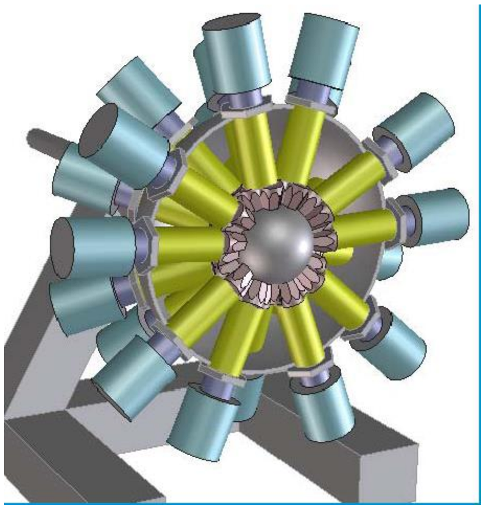


J. D. Holt et al., PRC 90 (2014)

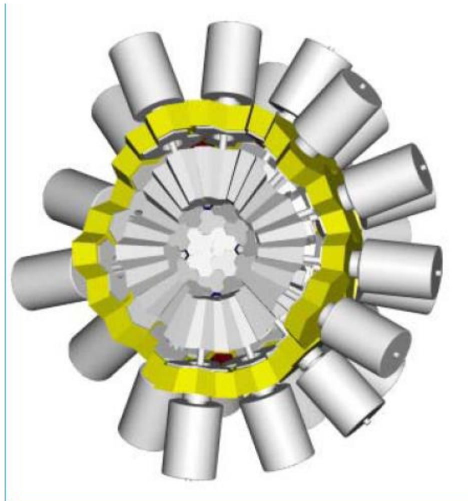
B.F. et al., PRC 77 (2008)

Gamma-ray spectroscopy of DIC products with radioactive beams

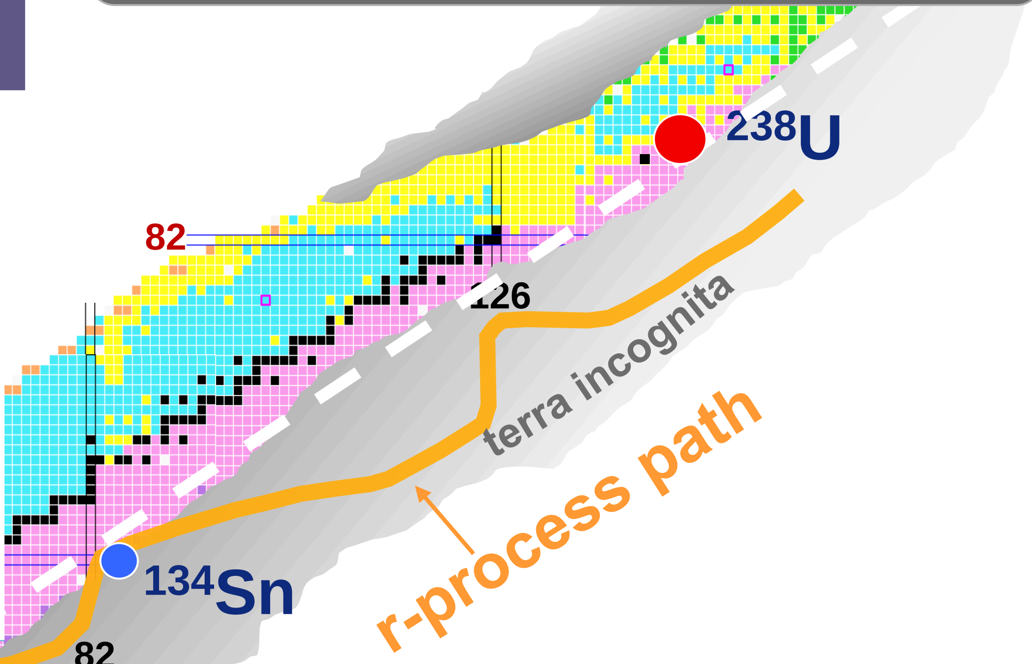
Gamma Arrays based on Position Sensitive Ge Detectors



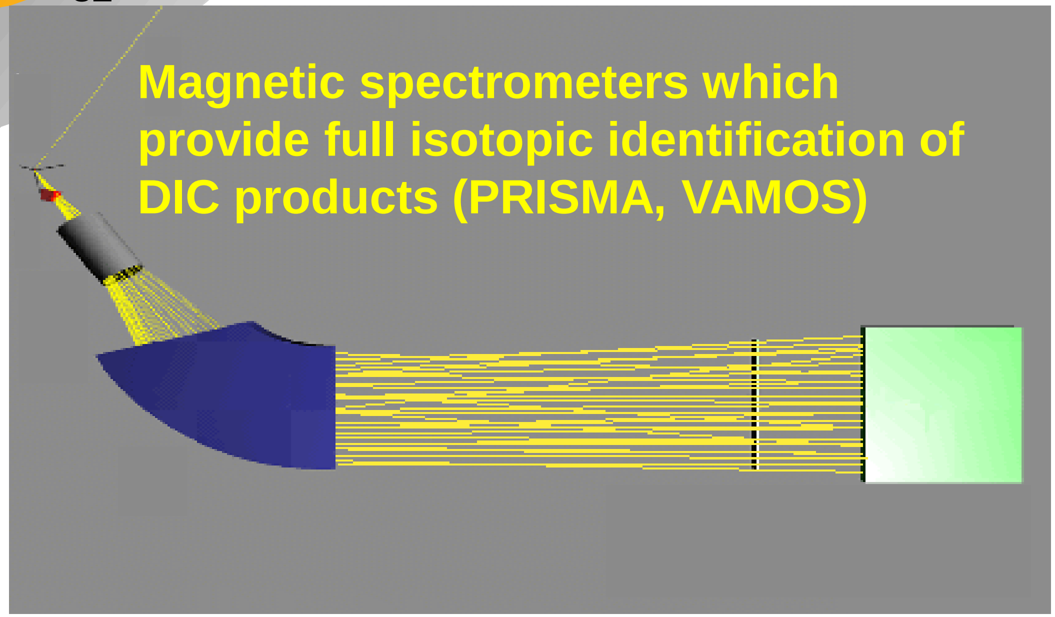
GRETA



AGATA



Magnetic spectrometers which provide full isotopic identification of DIC products (PRISMA, VAMOS)



Conclusions and Outlook

- Discrete in-beam gamma-ray spectroscopy with deep-inelastic reactions turned out to be efficient in elucidating high-spin structures in neutron-rich nuclei:
  - high-spin bands in neutron-rich Rn and Ra nuclei
  - identification of high-spin structures in nuclei around doubly-magic ^{208}Pb – those structures are well described by the shell-model calculations with the realistic nucleon-nucleon interaction derived from the free nucleon-nucleon potential
  - identification of the sub-shell gap at N=40 in Ni isotopes
  - observation of the sub-shell closure at N=32

- Discrete in-beam gamma-ray spectroscopy of deep-inelastic reactions products will greatly benefit from radioactive beams. Experiments using the radioactive beams and modern tracking germanium arrays should extend the investigations of high-spin structures toward the „terra incognita”.

“Reflections” in Liverpool

Reflections
on the atomic nucleus
Liverpool, 28-30 July 2015

Liverpool, 28-30 July 2015
on the atomic nucleus
Reflections

Waterfront reflections. Liverpool waterfront - a Unesco World Heritage site

Crosby beach, Liverpool

Echo and Narcissus
John William Waterhouse, 1903,
Walker Art Gallery, **Liverpool**

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